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## INTERIM NOTE ON AN INVESTIGATION OF THE LIABILITY TO "SHATTER" OF HIGH-STRENGTH LIGHT-ALLOY SHEET WHEN SUBJECT TO GUNFIRE

by

T.L.HUGHES, B.Sc.(Eng.)

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ROYAL AIRCRAFT ESTABLISHMENT, FARNBOROUGH

# Interim Note on an Investigation of the Liability to "Shatter" of High-Strength Light-Alloy Sheet when subject to Gunfire

by

T. L. Hughes, B.Sc.(Eng.)

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R.A.E. Ref: M.E./B3/9018/TLH

SUMMARY

This Note describes the progress of work on an investigation into the liability to "shatter" of high-strength light-alloy sheet materials when damaged by gunfire. Examination has been made of the physical properties and shatter characteristics of sheets of three thicknesses to British Specification D.T.D.687 and to the equivalent U.S. Specification AN-A-10(b) - referred to as 75 ST - as produced by four different manufacturers.

It was found that, under some conditions of attack, a small proportion of the samples of D.T.D.687 sheet - but not of 75 ST sheet - were liable to widespread failure by "shatter", and that a larger proportion, including both D.T.D.687 and 75 ST specimens, failed by splitting. The causes of the "shatter" phenomena are not yet known.

To avoid the inadvertent introduction, in the future, of high-strength light-alloy materials having more serious and completely unacceptable "shatter" characteristics, it is considered important to continue the investigation, with both sheet and extrusions, to establish the features responsible for the "shatter" effects. Further experimental work is planned, in particular to investigate the influence of certain of the chemical constituents on the "shatter" and splitting characteristics.

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LIST OF CONTENTS



LIST OF TABLES

## LIST OF APPENDICES



## LIST OF ILLUSTRATIONS

## 1 Introduction

The investigation described in this Note was initiated early in 1951, following American reports that structures in high-strength light-alloy sheet material, (type 75 ST) had failed by shatter when subjected to the blast from high-explosive charges. In addition there was limited evidence that the impact of a 20 mm solid shot on an unstressed plate of the same material had also caused shatter.

As the British high-strength light-alloy sheet to Specification D.T.D.687 is broadly similar to the American 75 ST sheet (see Appendix I), and is being used increasingly in Military aircraft, it was important to establish whether, and to what extent, a hazard due to shatter was introduced thereby.

Very limited preliminary trials were made[1] while arrangements were in hand to obtain large quantities of material for a comprehensive investigation into the problem of "shatter". The progress and results, to date, of the comprehensive investigation are recorded in this Note.

## 2 Range of Materials Tested

Samples of high-strength light-alloy sheet to the British Specification D.T.D.687, and/or to the American Specification AN-A-10(b) (Clad 75 ST - see Appendix I for details) were obtained from the following sources:-

The Northern Aluminium Co. Ltd. and Messrs. James Booth and Co. Ltd. both supplied typical production sheets to Specification D.T.D.687, in 16 S.W.G. (0.064 in.), 10 S.W.G. (0.128 in.) and 3/16 in. thicknesses.

The British Aluminium Co. Ltd. supplied sheets to Specifications D.T.D.687 and AN-A-10(b) in 16 S.W.G., 10 S.W.G. and 3/16 in. thicknesses, each in three types - differing in analysis but within the Specification limits - such that,

Type A had mechanical properties just satisfying the minimum requirements of the Specification,

Type B possessed mechanical properties typical of normal production sheet,

and Type C possessed the highest proof stress and ultimate tensile stress value obtainable by increasing the alloying elements to the maximum permitted by the Specification or to the maximum allowable for production reasons.

In addition, each type was supplied in two groups, differing slightly in the planishing and precipitation treatment.

Sheets of 75 ST, of American manufacture, in 16 S.W.G. and 10 S.W.G. thicknesses, were obtained from Whitehead Metals Inc., U.S.A.

Details of the analyses, manufacturing processes and mechanical properties of the specimens are given in Appendix II.

## 3 Trials Procedure and Results

The trials were made in a number of stages which are detailed in the following paragraphs:-

### 3.1 Firings against unstressed plates with 20 mm solid ammunition

For the purpose of the trials test specimens were cut 2 ft square and clamped in a rigid frame. Each specimen was attacked with a single round of 20 mm ball ammunition at its approximate centre, the angle of attack being 45° or 60° to the normal to the plate.

47 plates were attacked in this manner (see Table I). There was no evidence of shatter. Typical damage is illustrated in Figs.1 to 5.

### 3.2 Firings against unstressed plates with Hispano 20 mm explosive shell (direct attack)

Using the same simple arrangement as above, a number of selected specimens were attacked directly (i.e. without a "burster" plate) with 20 mm Hispano H.E./I shell fitted with Type 254 fuze. Owing to the relative insensitivity of the fuze, firings were made against the thicker gauges of plate only (angle of attack 45°).

Detailed results are recorded in Table II, and selected photographs reproduced in Figs.6 to 8.

In the 16 firings made, there was no evidence of shatter, but severe cracking occurred at the wound in one instance.

During this part of the trial, a 3/16 in. thick plate (manufactured by the British Aluminium Co. Ltd. to Specification D.T.D.687, Analysis B) which had previously been attacked directly with a 20 mm H.E./I round, was later subjected to the side-spray fragmentation and blast from the same type of shell. Long cracks were produced in the plate (see Fig.9).

### 3.3 Firings against tension stressed plates with 20 mm solid ammunition

Shaped tensile specimens, of 24" width in the test section, were loaded in a specially designed test-rig (described in Appendix III) and attacked, while stressed, with 20 mm ball ammunition - approximately centrally (at the "waist" of the specimen) and normal to the plate. A total of 102 specimens (including 3 control specimens of D.T.D.603 sheet) were tested in this manner, whilst loaded to various values between 35% and 85% of the specified ultimate tensile strength. The results are recorded in Tables III, IV and V.

Two distinct types of failure were evident, these were designated "split" and "shatter". Typical examples are shown in Figs.10(a) and (b) respectively. In no case however did a plate completely disintegrate.

Three specimens of 16 S.W.G., D.T.D.687 material manufactured by the British Aluminium Co. to Analyses C1 and C2 were attacked with 0.303 calibre ammunition (included in Table III). In the former case the failing load was lowered, while in the latter case it appeared to be raised.

The results may be summarised as follows:-

| Thickness of Sheet | No. of Sheets Attacked | No. of Sheets: Shattered | Split | Holed |
|---|---|---|---|---|
| (a) British Aluminium Co's. D.T.D.687 sheet | | | | |
| 3/16" | 11 | 1(Type C1) | - | 10 |
| 10 S.W.G. | 15 | 5(4 of Type C1) (1 of Type C2) | - | 10 |
| 16 S.W.G. | 19 | - | 9(2 of Type B1) (3 of Type B2) (3 of Type C1) (1 of Type C2) | 10 |
| (b) British Aluminium Co's. 75 ST sheet | | | | |
| 3/16" | 6 | - | - | 6 |
| 10 S.W.G. | 8 | - | - | 8 |
| 16 S.W.G. | 14 | - | 5(4 of Type C1) (1 of Type C2) | 9 |
| (c) Miscellaneous (3 of B.A. Co's. D.T.D.603 sheet; 8 of N.A. Co's. D.T.D.687 sheet; 10 of J.B.& Co's. D.T.D.687 sheet; 8 of U.S.A., 75 ST sheet) | | | | |
| 3/16" | 5 | - | - | 5 |
| 10 S.W.G. | 8 | - | - | 8 |
| 16 S.W.G. | 16 | - | 10(2 of N.A.687) (4 of J.B.687) (4 of U.S.A./75 ST) | 6 |
| TOTALS | 102 Attacks | 6 Shattered | 24 Split | 72 Holed |

It will be noted that Shatter was only experienced with 6 specimens, confined to 3/16" and 10 S.W.G. thicknesses of D.T.D.687 sheet of the "high-strength" type (analyses C1 and C2). These 6 specimens were stressed, variously, to between 60% and 85% of the ultimate tensile strength when attacked.

Splitting occurred with 24 of the specimens, all of 16 S.W.G. thickness and of each suppliers manufacture. The sheets which failed by splitting were stressed, when attacked, to values between 40% and 80% of the ultimate tensile strength.

3.4 Fragment firings against tension stressed plates

Using the same loading rig as before, stressed plates were attacked with single 1/25 oz. fragments at two velocities, 2500 ft/sec and 5,200 ft/sec. The fragments which were of cuboidal form (approximately 0.2 in. side) were manufactured from steel to Specification D.T.D.124 (45 tons/sq in. Ultimate Tensile Strength).

Each fragment was inserted in a plastic sabot of approximately $\frac{1}{8}$ oz. weight, and fired from an 0.5 in. calibre Browning gun. The sabot was stopped by a steel plate and the fragment allowed to pass on through a small hole. The "stop plate" was completely effective in only about 50% of the tests, and the specimen sheets were, therefore, frequently struck by both the fragment and pieces of sabot.

Firings were made normal to the plate, against 16 S.W.G. American 75 ST and against 16 S.W.G. D.T.D.687 supplied by the Northern Aluminium Co. Ltd., which had split at 50% and 60% U.T.S. respectively when attacked with 20 mm ball ammunition. Some firings were also made against 10 S.W.G. material to Specification D.T.D.687, Analysis C2, supplied by the British Aluminium Co. Ltd.

The results are recorded in Table VI and illustrated in Figs.11 and 12. No instance of shatter occurred, but, of 11 specimens attacked, 5 failed by splitting. Except in one case, failure did not occur when a plate was struck by a fragment alone, even when stressed to either 70% or 80% of the U.T.S. When plates at these same stresses were holed by pieces of sabot, in addition to the fragment, failure by splitting occurred in every case. Where the sabot inadvertently struck the specimen, a double wound as well as a much higher impact energy were naturally involved.

3.5 Firings against unstressed plates with 20 mm Mauser explosive shell (detonation remote from plate)

For these firings, German Mauser 20 mm H.E./I shell, fitted with fuze AZ.1504, were fired from a range of 35 yards, at thin "burster" plates (20 S.W.G. Dural) placed at between 13 and 19 inches from the test plates (normal to the line of fire). The shell detonated consistently two to three inches after first impact. These tests simulated detonation of a shell inside an aircraft structure, the plate being subjected to both the blast load and the fragmentation from the shell.

The results of the firings are recorded in Table VII and photographs of damaged plates are reproduced in Figs.13 to 16.

In these tests, the form of failure was somewhat different to the simple "splitting" and "shatter" referred to in paragraph 3.3. It was decided to retain and broaden the previously adopted categories of damage, as detailed below, though it is appreciated that further sub-division of the forms of damage, by the introduction of new categories, may be needed eventually.

"Shatter": Disintegration of the specimen, or
Damage causing the plate to split into three or more large pieces, or
Damage by fragment wounds plus multiple and widespread cracking (ref. Fig.15b), or
Fragment wounds plus a full-width split and minor cracking (ref. Fig.14a).

"Split": Failure by a single split across the plate, or
Fragment wounds plus a simple split across the specimen (ref. Fig.13c).

"Holed": A single wound with not more than minor edge-cracks, or
Fragment wounds, including - in some instances - small cracks joining pairs of wounds (ref. Fig.14b).

The results of the firings may be summarised as follows:-

| Thickness of Sheet | No. of Sheets Attacked | No. of Sheets: Shattered | Split | Holed |
|---|---|---|---|---|
| 3/16" | 5 | 2(One B.A.687 Type C1) (One J.B.687) | 1(N.A.687) | 2 |
| 10 S.W.G. | 6 | 1(J.B.687) | - | 5(Inc. one of D.T.D.603) |
| 16 S.W.G. | 2 | 1(B.A.687 Type C2) | - | 1(D.T.D.603) |
| TOTALS: | 13 Attacks | 4 Shattered | 1 Split | 8 Holed |

Two sheets of D.T.D.603 material were included in these firings, to give a basis for comparison.

Although relatively few firings have yet been made in this particular series, there is a slight indication that D.T.D.687 sheet of each of the three thicknesses tested is liable to shatter under this form of attack, even when in an unstressed state. Two of the four sheets which shattered were of the "high-strength" type (analyses C1 and C2). Neither of the two D.T.D.603 sheets shattered or split in the tests.

## 4 Discussion of Results

The approximate order of susceptibility to failure of the materials when subject to gunfire is best shown by results of firings against stressed plates with 20 mm solid shot. The materials which failed under attack when stressed to less than 80% U.T.S. are tabulated below (extracted from Tables III, IV and V).

| Thickness | Material: Manufactured by:- | Spec. | Analysis | Critical Stress Region % U.T.S.: No Failure | Failure | Type of Failure |
|---|---|---|---|---|---|---|
| 16 S.W.G. (0.064 in) | Messrs. James Booth & Co. Ltd. | D.T.D.687 | - | 40 | 40 | Split |
| | British Aluminium Co. Ltd. | D.T.D.687 | C1 | 43 | 54 | Split |
| | British Aluminium Co. Ltd. | D.T.D.687 | C2 | 40 | 50 | Split |
| | British Aluminium Co. Ltd. | D.T.D.687 | B1 | 43 | 53 | Split |
| | British Aluminium Co. Ltd. | D.T.D.687 | B2 | 40 | 50 | Split |
| | U.S.A. | 75 ST | - | 40 | 50 | Split |
| | British Aluminium Co. Ltd. | 75 ST | C1 | - | 60 | Split |
| | British Aluminium Co. Ltd. | 75 ST | C2 | 50 | 80 | Split |
| | Northern Aluminium Co. Ltd. | D.T.D.687 | - | 60 | 60 | Split |
| 10 S.W.G. (0.128 in.) | British Aluminium Co. Ltd. | D.T.D.687 | C1 | - | 60 | Shatter |
| | British Aluminium Co. Ltd. | D.T.D.687 | C2 | 66 | 77 | Shatter |
| 3/16" | British Aluminium Co. Ltd. | D.T.D.687 | C1 | 70 | 70 | Shatter |

It was observed during the trials that some plates, particularly in the thicker gauges, had a tendency to flake on the exit side, when attacked in an unstressed state with 20 mm solid shot. The extent of flaking appeared to be greatest with the materials which, in other tests, appeared most susceptible to failure by "shatter" or "splitting" (see Figs.1 to 5).

The liability of particular sheets to "shatter" or "split" was confirmed by the firings in which Mauser 20 mm H.E./I shell were detonated a short distance from unstressed plate specimens. Under these conditions some of the thicker materials failed, more particularly those materials which had failed, in the thinner gauges, at relatively low loads, when attacked with 20 mm solid shot.

The mechanism of failure under these conditions of attack is not fully understood, but it is possible that the shell fragments struck when the plates were momentarily in a highly stressed state due to blast loading from the shell.

In contrast, when 20 mm H.E./I shell were fired to detonate directly on unstressed plates, the resulting damage was usually confined to a hole 2 to 3 in. in diameter. In these tests it is probable that the hole was produced entirely by blast effect, and the fragments, being projected forward, did not strike the target plate.

Throughout the trials, the majority of specimens for loading were made so that the load was applied in the direction of final rolling. Some firings were made against specimens loaded perpendicular to the direction of final rolling (noted in Tables IV and V) but insufficient firings were made to come to any definite conclusion as to the effect of rolling direction on the strength of the sheet under attack.

The results obtained so far may be summarised as follows:-

Of 184 firings made against samples of D.T.D.687 and 75 ST sheet, a total of 10 specimens ($5\frac{1}{2}$%) failed by "shatter" - none of these was of 75 ST material of either British or U.S. manufacture - and 31 specimens (17%) failed by splitting - including 11 of 75 ST sheet (6 British and 5 U.S. manufacture).

There is little evidence, so far, of any precise relationship between the mechanical properties of the materials and their susceptibility to failure under gunfire. This problem, and the effect of variations in the chemical analyses, are matters for further investigation, and are being studied both by the Inter-Services Metallurgical Research Council and the R.A.E.

The stresses to which the plates were subjected in some of the trials were generally high compared with those likely to be encountered in an aircraft under normal flight conditions, and were employed only for convenience in comparing the properties of the various materials. In future trials, it is proposed that the plates shall be stressed to not more than 30% of the ultimate tensile stress, attacks being made with 20 mm Mauser H.E./I ammunition (as described in para.3.5). The limit of 30% U.T.S. covers conditions in bomber and transport aircraft structures during level flight (compared with less than 10% U.T.S. in fighters), though stresses as high as 67% of the U.T.S. can be encountered for short periods of time in both bomber and fighter aircraft.

## 5 Further Development

The results obtained so far do not indicate an alarming position regarding the collapse, by projectile damage, of structures in D.T.D.687

alloy. Nevertheless, it is evident that widespread failure can occur by "shatter" in some circumstances, and with some particular forms of D.T.D.687 sheet. In order to avoid the development of high-strength light-alloy materials having serious "shatter" characteristics, it is considered imperative to continue the investigation, with both sheet and extrusions, until the features responsible for the "shatter" effects can be established.

Trials against both stressed and unstressed plates, using remotely detonated 20 mm H.E./I shell, are therefore continuing, and a number of firings against extruded sections in D.T.D.683 will be included shortly.

It is planned to make similar trials to investigate the effects of varying the chemical constituents of the materials within the limits of Specification D.T.D.687, in particular, the effects of varying the percentages of zinc and magnesium.

Acknowledgements

Acknowledgement is made of the welcome collaboration and assistance provided, throughout the investigation, by the Chairman and Members of the British Non-Ferrous Metals Research Association, and by the Directors of the following firms:-

The British Aluminium Co. Ltd.
Messrs. James Booth & Co. Ltd.
The Northern Aluminium Co. Ltd.

REFERENCE

| No. | Author | Title, etc. |
| --- | --- | --- |
| 1 | T.L. Hughes | R.A.E. Test Note No. Mech. Eng.314 entitled "Trials to investigate the possibility of "shatter" of high-strength light-alloy sheet to Specification D.T.D.687". |

Attached: Tables I to VII Detachable Abstract Cards
Appendix I
" II
" III with Dwgs. No.
SME 75005 and 75006
and Negs. No. 108880 and 108896

Advance Distribution:

DGTD(A)
PDSR(A)
PDRD(A)
D Mat RD - Action
DARD
DMARD(RAF)
DMARD(RN)
DDARD
ADR Structures
The Secretary Ordnance Board - 2
TPA3/TIB - 95

Director RAE
DDRAE(A)
DDRAE(E)
Head of Metallurgy Dept
Head of Structures Dept
Secretary RAE Vulnerability and Lethality Working Party
RAE Library
NAE Library

## TABLE I

### List of firings against unstressed plates of high-strength light-alloy

**Ammunition:- 20 mm Ball**

| Manufacturer | Specification | Sheet Thickness | Analysis (see Appendix "II") | Angle of Attack ° to Normal | No. of Firings | Photograph |
|---|---|---|---|---|---|---|
| The British Aluminium Co. Ltd. | D.T.D.687 | 3/16 in. | A1 | 60° | 1 | Fig.1(a) |
| | | | A2 | 60° | 1 | |
| | | | B1 | 60° | 1 | Fig.1(b) |
| | | | B2 | 60° | 1 | |
| | | | C1 | 60° | 1 | Fig.1(c) |
| | | | C2 | 60° | 1 | |
| | | 10 S.W.G. | A1 | 60° | 1 | |
| | | | A2 | 60° | 1 | |
| | | | B1 | 60° | 1 | |
| | | | B2 | 60° | 1 | |
| | | | C1 | 60° | 1 | |
| | | | C2 | 60° | 1 | |
| | | 16 S.W.G. | A1 | 60° | 1 | |
| | | | A2 | 60° | 1 | |
| | | | B1 | 60° | 1 | |
| | | | B2 | 60° | 1 | |
| | | | C1 | 60° | 1 | |
| | | | C2 | 60° | 1 | |
| The British Aluminium Co. Ltd. | 75 ST | 3/16 in. | A1 | 60° | 1 | Fig.2(a) |
| | | | A2 | 60° | 1 | |
| | | | B1 | 60° | 1 | Fig.2(b) |
| | | | B2 | 60° | 1 | |
| | | | C1 | 60° | 1 | Fig.2(c) |
| | | | C2 | 60° | 1 | |
| | | 10 S.W.G. | A1 | 60° | 1 | |
| | | | A2 | 60° | 1 | |
| | | | B1 | 60° | 1 | |
| | | | B2 | 60° | 1 | |
| | | | C1 | 60° | 1 | |
| | | | C2 | 60° | 1 | |
| | | 16 S.W.G. | A1 | 60° | 1 | |
| | | | A2 | 60° | 1 | |
| | | | B1 | 60° | 1 | |
| | | | B2 | 60° | 1 | |
| | | | C1 | 60° | 1 | |
| | | | C2 | 60° | 1 | |
| The Northern Aluminium Co. Ltd. | D.T.D.687 | 3/16 in. | - | Normal | 1 | |
| | | | | 45° | 1 | Fig.3 |
| | | 10 S.W.G. | - | Normal | 1 | |
| | | | | 45° | 1 | |
| | | | | 60° | 1 | |
| | | 16 S.W.G. | - | 45° | 2 | |
| | | | | 60° | 1 | |
| Messrs. James Booth & Co. Ltd. | D.T.D.687 | 3/16 in. | - | 45° | 1 | Fig.4 |
| | | 10 S.W.G. | - | 45° | 1 | Fig.5(a) |
| | | 16 S.W.G. | - | 45° | 1 | Fig.5(b) |

Note: No evidence of "shatter" or serious splitting of the plates was observed in these tests.

## TABLE II

### Results of firings against unstressed plates of high-strength light-alloy

Ammunition:- 20 mm Hispano H.E./I
Fuze 254

Plates attacked directly at $45^\circ$ to normal
(i.e. no burster plate employed)

| Manufacturer | Material | Sheet Thickness | Analysis (see Appendix "II") | Result |
|---|---|---|---|---|
| The British Aluminium Co. Ltd. | D.T.D.687 | 3/16 in. | A1 | Hole 3 in. × 2 in. Little tendency to petal. Medium flaking of back surface. See Fig. 6(a). |
| | | 3/16 in. | B1 | Hole 3¼ in. × 2 in. No petalling. Medium flaking of back surface. |
| | | 3/16 in. | B2 | Hole 3½ in. × 2 in. No petalling. Medium flaking of back surface. See Fig. 6(b). |
| | | 3/16 in. | C1 | Hole 2 in. × 1½ in. No petalling or flaking. Shell appeared to have detonated when completely through plate. |
| | | 3/16 in. | C2 | Hole 3 in. × 3 in. No petalling. Flaking of back surface and some small (¾ in. to 1 in.) cracks. See Fig. 7. |
| | | 10 S.W.G. | C1 | 2 in. × 1½ in. hole. Shell detonated with comparatively long delay. |
| | | | C1 | 2½ in. × 2 in. hole. One 1 in. crack and two ½ in. cracks through plate. Medium flaking. |
| The British Aluminium Co. Ltd. | 75 ST | 3/16 in. | A1 | Hole 5 in. × 2½ in. One 1½ in. crack. Slight tendency to petal but mainly slightly flaked edge to hole. |
| | | 3/16 in. | B1 | Hole 3 in. × 3 in. Shell exploded with less delay than normal. Some flaking round edge of hole and some petalling. |
| | | 3/16 in. | B2 | Hole 2 in. × 3 in. Two 2 in. cracks and one 1½ in. crack. Some petalling of plate. |

TABLE II (CONTD)

| Manu-facturer | Material | Sheet Thickness | Analysis (see Appendix "II") | Result |
|---|---|---|---|---|
| The British Aluminium Co. Ltd. | 75 ST | 3/16 in. | C2 | Hole 3 in. × 3 in. No petalling. Flaking of back surface and some small cracks. |
| | | 10 S.W.G. | B1 | Hole $2\frac{1}{2}$ in. × $1\frac{1}{2}$ in. with six cracks from 1 in. to $4\frac{1}{2}$ in. long. Larger petals. Shell appeared to have detonated while in plate. See Fig. 8(b). |
| | | 10 S.W.G. | B1 | Hole 2 in. × 2 in. Little flaking. Two 1 in. cracks from hole. Shell appeared to have detonated when completely through plate. See Fig. 8(a). |
| | | 10 S.W.G. | B2 | Hole 2 in. × 2 in. with little flaking. One 1 in. crack. |
| | | 10 S.W.G. | C1 | Hole 3 in. × 2 in. A little flaking of the back surface and one 1 in. crack. |
| The Northern Aluminium Co. Ltd. | D.T.D. 687 | 3/16 in. | - | Hole $2\frac{1}{2}$ in. × 2 in. with little flaking or petalling. One 1 inch crack. |

## TABLE III

Firings against stressed plates of high-strength light-alloy

Material:- Supplied by the British Aluminium Co. Ltd. to Spec. D.T.D.687

Ammunition: 20 mm Ball and three rounds only of 0.303 A.P.

| Sheet Thickness | Analysis (see Appendix "II") | Stress on Sheet % U.T.S. | Result | Notes |
|---|---|---|---|---|
| 3/16 in. | A1 | 80 | Holed | |
| | A2 | 80 | Holed | |
| | B1 | 80 | Holed | |
| | B2 | 80 | Holed | |
| | C1 | 50 | Holed | |
| | | 60 | Holed | |
| | | 60 | Holed | |
| | | 70 | Shatter | |
| | | 70 | Holed | Attack 3" from edge of specimen |
| | C2 | 80 | Holed | Load held for 2 mins before firing |
| | | 80 | Holed | Load applied quickly |
| 10 S.W.G. | A1 | 70 | Holed | |
| | | 80 | Holed | |
| | | 80 | Holed | |
| | A2 | 80 | Holed | |
| | B1 | 30 | Holed | |
| | | 75 | Holed | |
| | | 85 | Holed | |
| | B2 | 80 | Holed | |
| | C1 | 60 | Shatter | |
| | | 75 | Shatter | |
| | | 75 | Shatter | |
| | | 85 | Shatter | |
| | C2 | 50 | Holed | |
| | | 66 | Holed | |
| | | 77 | Shatter | |
| 16 S.W.G. | A1 | 50 | Holed | |
| | | 60 | Holed | |
| | | 70 | Holed | |
| | | 80 | Holed | |
| | A2 | 80 | Holed | |
| | B1 | 43 | Holed and small cracks | |
| | | 53 | Split | |
| | | 60 | Split | |

TABLE III (CONTD)

| Sheet Thickness | Analysis (see Appendix "II") | Stress on Sheet % U.T.S. | Result | Notes |
|---|---|---|---|---|
| 16 S.W.G. | B2 | 40 | Holed | |
| | | 50 | Split | |
| | | 70 | Split | |
| | | 70 | Split | |
| | C1 | 43 | Holed | |
| | | 43 | Split | Attack with 0.303 AP |
| | | 54 | Split | |
| | | 54 | Split | Attack with 0.303 AP |
| | C2 | 40 | Holed | |
| | | 50 | Split | |
| | | 50 | Holed | Attack with 0.303 AP |

Tech. Note No. Mech. Eng. 155

TABLE IV

Firings against stressed plates of high-strength light-alloy

Material: Supplied by the British Aluminium Co. Ltd. to Spec. 75 ST

Ammunition: 20 mm Ball

| Sheet Thickness | Analysis | Stress on Sheet % U.T.S. | Result | Notes |
|---|---|---|---|---|
| 3/16 in. | A1 | 80 | Holed | |
| | A2 | 80 | Holed | |
| | B1 | 80 | Holed | |
| | B2 | 80 | Holed | |
| | C1 | 80 | Holed | |
| | C2 | 80 | Holed | |
| 10 S.W.G. | A1 | 80 | Holed | |
| | A2 | 80 | Holed | |
| | B1 | 75 | Holed | |
| | | 80 | Holed | |
| | B2 | 80 | Holed | |
| | C1 | 75 | Holed | |
| | | 80 | Holed | |
| | C2 | 80 | Holed | |
| 16 S.W.G. | A1 | 80 | Holed | |
| | | 80 | Holed | Load applied at right angles to direction of rolling |
| | A2 | 80 | Holed | |
| | B1 | 50 | Holed | |
| | | 60 | Holed | |
| | | 70 | Holed | |
| | | 80 | Holed | |
| | B2 | 80 | Holed | |
| | C1 | 60 | Split | |
| | | 70 | Split | |
| | | 70 | Split | |
| | | 80 | Split | |
| | C2 | 50 | Holed | |
| | C2 | 80 | Split | |

TABLE V

Firings against stressed plates of high-strength light-alloy

Materials:- Miscellaneous

Ammunition:- 20 mm Ball

| Alloy Manufacturer and Spec. | Sheet Thickness | Stress on Sheet % U.T.S. | Result | Notes |
|---|---|---|---|---|
| The British Aluminium Co. Ltd. *D.T.D.603 | 3/16 in. | 80 | Holed (slightly petalled) | |
| | 10 S.W.G. | 80 | Holed (petalled) | |
| | 16 S.W.G. | 80 | Holed (petalled) | |
| The Northern Aluminium Co. Ltd. D.T.D.687 | 3/16 in. | 80 | Holed | |
| | 10 S.W.G. | 60<br>70<br>80 | Holed<br>Holed<br>Holed | |
| | 16 S.W.G. | 50<br>60 | Holed<br>Split | |
| | | 60<br>70 | Holed<br>Split | Tension applied at right angles to direction of rolling |
| Messrs. James Booth & Co. Ltd. D.T.D.687 | 3/16 in. | 50<br>60<br>70 | Holed<br>Holed<br>Holed | |
| | 10 S.W.G. | 80 | Holed | |
| | 16 S.W.G. | 35<br>40<br>40 | Holed<br>Holed<br>Split | Tension applied at right angles to the direction of rolling |
| | | 50<br>60<br>70 | Split<br>Split<br>Split | |
| Whitehead Metals Inc. U.S.A. 75 ST | 10 S.W.G. | 50<br>80 | Holed<br>Holed | Tension applied at right angles to direction of rolling |
| | | 80 | Holed | |
| | 16 S.W.G. | 40<br>50<br>60<br>70<br>80 | Holed<br>Split<br>Split<br>Split<br>Split | Tension applied at right angles to direction of rolling |

*Note: Sheets to Spec. D.T.D.603 were included here as control specimens.

TABLE VI

Firings against stressed plates of high-strength light-alloy

Ammunition:- 1/25 oz. fragments at 2,500 ft/sec and 5,200 ft/sec

Note: The fragment was inserted in a plastic sabot of approximately $\frac{1}{8}$ oz. weight and fired from a 0.5 in. Browning gun. The sabot was stopped by a steel plate while the fragment was allowed to pass through a small hole. The "stop plate" was effective in about 50% of the cases.

| Alloy Manufacturer Specification and Thickness | Stress on Sheet % U.T.S. | Nominal Conditions of Attack | Results |
|---|---|---|---|
| The Northern Aluminium Co. Ltd. D.T.D.687 16 S.W.G. | 60 | 1/25 oz. at 2,500 ft/sec | Fair Hit - Plates holed only |
| | 70 | 1/25 oz. at 5,200 ft/sec | Plate holed by fragment and piece of sabot. Split across plate originating at hole by sabot See Fig.11(a) |
| | 70 | 1/25 oz. at 2,500 ft/sec | Plate holed by fragment, dented by piece of sabot |
| | 80 | 1/25 oz. at 2,500 ft/sec | Fair Hit - Plate holed only |
| | 80 | 1/25 oz. at 5,200 ft/sec | Fair Hit - Plate holed. Some very fine cracks about $\frac{1}{4}$ in. - $\frac{1}{2}$ in. long radiating from hole |
| | 80 | 1/25 oz. at 5,200 ft/sec | Plate holed by fragment and piece of sabot. Split originating at latter hole See Fig.11(b) |
| Whitehead Metals Inc. U.S.A. 75 ST 16 S.W.G. | 70 | 1/25 oz. at 5,200 ft/sec | Fair Hit - Plate holed only |
| | 80 | 1/25 oz. at 5,200 ft/sec | Fragment passed through 3/16 in. stop-plate* before striking target. Plate holed by fragment and split |
| The British Aluminium Co. Ltd. D.T.D.687 Analysis C2 10 S.W.G. | 80 | 1/25 oz. Fragment and Sabot at 5,200 ft/sec | Fragment and sabot did not separate. Hole $1\frac{1}{2}$ in. dia. Split originating at hole |
| | 80 | 1/25 oz. at 5,200 ft/sec | Fair Hit - Fragment hole only See Fig.12(a) |
| | 80 | 1/25 oz. at 5,200 ft/sec | Holes by fragment and pieces of sabot. Split and crack both originating at sabot holes See Fig.12(b) |

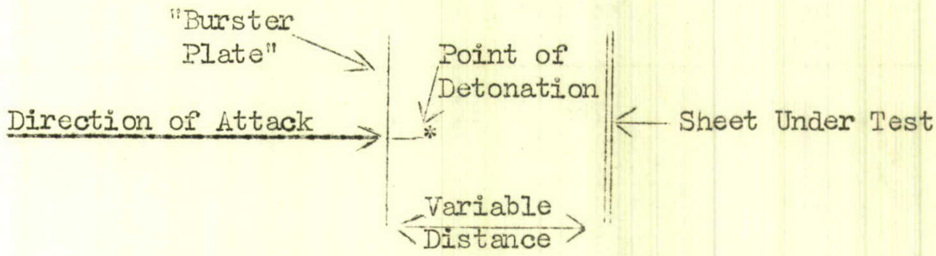
*Note: In this firing a further "stop-plate" of 3/16 in. Dural was introduced in an attempt to stop fragments of sabot from striking the plate under test.

## TABLE VII

Firings against unstressed plates of high-strength light-alloy with 20 mm Mauser H.E./I ammunition

Shell Fuze:- Sensitive, and operates when shell is just through "burster plate"

Target arrangement:




| Firing No. | Distance of Burster Plate to Specimen Under Test | Sheet Under Test Manu-facturer | Material | Thickness | Analysis (see App. II) | Result |
|---|---|---|---|---|---|---|
| 1 | 17 in. | The British Al. Co. Ltd. | D.T.D.687 | 3/16 in. | C1 | "Shatter"* (see Fig.13(a)) |
| 2 | 19 in. | The British Al. Co. Ltd. | D.T.D.687 | 3/16 in. | A2 | Fragment Damage Only (see Fig.13(b)) |
| 3 | 13 in. | The Northern Al. Co. Ltd. | D.T.D.687 | 3/16 in. | - | Split (see Fig.13(c)) |
| 4 | 13 in. | Messrs. James Booth & Co. Ltd. | D.T.D.687 | 3/16 in. | - | "Shatter" (see Fig.14(a)) |
| 5 | 19 in. | Messrs. James Booth & Co. Ltd. | D.T.D.687 | 3/16 in. | - | Fragment Damage Only (See Fig.14(b)) |
| 6 | 19 in. | The Northern Al. Co. Ltd. | D.T.D.687 | 10 S.W.G. | - | Fragment Damage Only (See Fig.14(c)) |
| 7 | 19 in. | Messrs. James Booth & Co. Ltd. | D.T.D.687 | 10 S.W.G. | - | "Shatter" (see Fig.15(a)) |

Note: *The damage, in this case, was somewhat less than a true "shatter" effect, and might be better termed "widespread cracking".

TABLE VII (CONTD)

| Firing No. | Distance of Burster Plate to Specimen Under Test | Sheet Under Test Manufacturer | Material | Thickness | Analysis (see App. II) | Result |
|---|---|---|---|---|---|---|
| 8 | 19 in. | The British Al. Co. Ltd. | D.T.D.687 | 16 S.W.G. | C2 | "Shatter" (see Fig.15(b)) |
| 9 | 19 in. | The British Al. Co. Ltd. | D.T.D.603[xx] | 16 S.W.G. | - | Fragment Damage Only (see Fig.15(c)) |
| 10 | 16 in. | The Northern Al. Co. Ltd. | D.T.D.687 | 10 S.W.G. | - | Fragment Damage Only (see Fig.16(a)) |
| 11 | 13 in. | The British Al. Co. Ltd. | D.T.D.603[xx] | 10 S.W.G. | - | Fragment Damage Only (see Fig.16(b)) |
| 12 | 13 in. | The British Al. Co. Ltd. | D.T.D.687 | 10 S.W.G. | A1 | Fragment Damage Only (See Fig.16(c)) |
| 13 | 13 in. | Messrs. James Booth & Co. Ltd. | D.T.D.687 | 10 S.W.G. | - | Fragment Damage Only |

Note: [xx]Two sheets of D.T.D.603 material were included as control specimens.

## APPENDIX I

### A Comparison of the Properties of Light-Alloy "75 ST" (U.S.A.) and British Light-Alloy to Specification D.T.D.687

| | AMERICAN MATERIALS | | BRITISH MATERIALS |
|---|---|---|---|
| | Specification AN-A-9(a) (NOT CLAD) | Specification AN-A-10(b) (CLAD) | Specification D.T.D.687 (CLAD) |
| **Chemical Analysis:-** | | | |
| Zinc | 5.1 - 6.1% | 5.1 - 6.1% | 4.5 - 6.5% |
| Magnesium | 2.1 - 2.9 | 2.1 - 2.9 | 2.0 - 3.5 |
| Copper | 1.2 - 2.0 | 1.2 - 2.0 | 1.5 max. |
| Chromium | 0.15 - 0.40 | 0.15 - 0.40 | 0.5 max. |
| Manganese | 0.30 max. | 0.30 max. | 0.30 - 1.0 |
| Iron | 0.70 max. | 0.70 max. | 0.5 max. |
| Silicon | 0.50 max. | 0.50 max. | 0.5 max. |
| Titanium | 0.20 max. | 0.20 max. | 0.3 max. |
| Others each | 0.05 max. | 0.05 max. | - |
| Others total | 0.15 max. | 0.15 max. | - |
| Aluminium | Remainder | Remainder | Remainder |
| **Chemical Composition of Coating Alloy:-** | | | |
| Zinc | | 0.75 - 1.25% | 0.8 - 1.2 |
| Magnesium | | 0.10 | - |
| Copper | | 0.10 max. | - |
| Manganese | | 0.10 max. | - |
| Silicon | | 0.7 | - |
| Others total | | 0.15 | - |
| Aluminium | | Remainder | Remainder |
| **Physical Properties:-** | Data below is given for thickness between 19 S.W.G. (0.04") and 7/0 S.W.G. (0.50"). | | Data for thickness greater than 21 S.W.G. (0.032"). |
| U.T.S. | 34.4 t./sq.in. | 32.1 t./sq.in. | 32 t./sq.in. |
| Proof Stress | (0.2%) 29.4 t./sq. in. | (0.25%) 27.7 t./sq.in. | (0.1%) 27 t./sq.in. |
| Elongation | 8% | 8% | 8% for gauges greater than 12 S.W.G. |
| **Heat Treatment** | (In accordance with U.S.A. Spec. AN-QQ-H-186) Sheets solution treated at 460°C to 489°C and precipitation treated by heating to 118.5°C to 124°C for 24 hours. | | Sheets solution treated at 465°C ± 5°C, quenched and then precipitation treated by heating between 110°C and 140°C for the "requisite period". |

## APPENDIX II

### Details of Materials Supplied for Testing

James Booth & Co., Ltd. Sheets of 16 S.W.G., 10 S.W.G. and 3/16 in. were provided, the following being the cast analyses:-

| | Cu | Mn | Mg | Fe | Si | Zn | Ti | Cr |
|---|---|---|---|---|---|---|---|---|
| 16 S.W.G. | 0.97 | 0.36 | 2.93 | 0.28 | 0.14 | 5.68 | 0.09 | 0.07 |
| 10 S.W.G. | 1.04 | 0.35 | 3.07 | 0.24 | 0.16 | 5.94 | 0.06 | 0.07 |
| 3/16 in. | 0.96 | 0.34 | 2.78 | 0.19 | 0.14 | 6.02 | 0.06 | 0.07 |

The sheets were solution treated at 460°C and precipitated for 12 hours at 135°C.

The following are the manufacturing details of the sheets:-

All this material was made from cast slab 30" wide x 8" thick. Prior to hot rolling the slab was milled to 7" thick. They were then hot rolled down to $\frac{1}{4}$" thickness at 30" wide and the plates were then cut up into suitable pieces for subsequent cold rolling. Hot rolling was carried out at 420°C. The following are the cold rolling schedules:

1. 72" x 36" x 0.187"

    0.25" thick plates annealed 360°C.
    Cold rolled to 0.187" thick.
    Edges trimmed.
    Solution treated 460°C x 20 mins. (in salt).
    Stretched sufficiently to make flat.
    Cut to size.
    Precipitated 135°C x 12 hours.

2. 72" x 36" x 0.064"

    0.25" thick plates annealed (360°C).
    Cold rolled to 0.130" thick.
    Annealed 360°C.
    Cold rolled to 0.107" thick.
    Annealed 360°C.
    Cold rolled to 0.064" thick.
    Edges trimmed.
    Solution treated 460°C x 30 mins. (in salt).
    Stretched sufficiently to make flat.
    Cut to size.
    Precipitated 135°C x 12 hours.

3. 72" x 36" x 0.128"

    0.25" thick plates annealed 360°C.
    Cold rolled to 0.150" thick.
    Annealed 360°C.
    Cold rolled to 0.128" thick.
    Edges trimmed.
    Solution treated 460°C x 40 mins. (in salt).
    Stretched sufficiently to make flat.
    Cut to size.
    Precipitated 135°C x 12 hours.

British Aluminium Co., Ltd. This firm kindly supplied sheets of 16 S.W.G., 10 S.W.G. and 3/16 in. D.T.D.687 and also the same thicknesses in the equivalent American 75ST alloy. Furthermore, the firm also undertook to supply three compositions in both alloy types to represent low magnesium combined with low zinc, average magnesium and zinc and high magnesium combined with high zinc, in each case, the actual composition being within specification limits. The following were the chemical analyses reported:-

| D.T.D.687 | Cu | Mn | Mg | Fe | Si | Zn | Cr |
|---|---|---|---|---|---|---|---|
| Type A | 1.22 | 0.35 | 2.19 | 0.18 | 0.11 | 5.11 | - |
| " B | 1.37 | 0.45 | 2.56 | 0.23 | 0.13 | 5.69 | - |
| " C | 1.28 | 0.35 | 3.28 | 0.17 | 0.11 | 5.87 | - |
| 75ST | | | | | | | |
| Type A | 1.65 | 0.21 | 2.47 | 0.19 | 0.12 | 5.25 | 0.25 |
| " B | 1.77 | 0.21 | 2.50 | 0.14 | 0.13 | 5.59 | 0.26 |
| " C | 1.84 | 0.21 | 2.81 | 0.20 | 0.11 | 5.91 | 0.28 |

The procedure used in manufacture was experimental so as to provide the required range of properties, the following being the details supplied by the firm:-

"The whole of the blocks in both types of alloy were prepared by the semi-continuous casting process and after cutting to length were homogenised at 430°C for 10 hours and were clad with 1% zinc plates.

The blocks were hot rolled in two stages to a thickness of 0.220", the preheating temperature being designed so that rolling could be carried out in a temperature range 380-400°C.

After cooling the blanks were cut for cold rolling and the following treatment was given:

| | |
|---|---|
| Finishing Gauge 0.064" | Blanks annealed, rolled to 0.120", annealed, and rolled to 0.064". |
| Finishing Gauge 0.128" | Blanks annealed, rolled to 0.128". |
| Finishing Gauge 0.187" | Blanks rolled without an anneal to 0.187". |

In all cases the annealing was done in a muffle for 6 hours at a zone setting of 420°C.

The sheets were solution treated at the finishing gauge at 465° ± 5°C for both alloys, the soaking times being 18 mins., 40 mins. and 45 mins. for the three gauges respectively.

Following the solution treatment each type of metal was divided into two groups, differing slightly in the planishing and precipitation treatment; the details are as follow:

D.T.D.687A Type A

Group 1. Planishing (1% to 2% reduction) and stretching, followed by artificial ageing (8 hours 130° - 140°C).

Group 2. Roller levelling and stretching, followed by artificial ageing for 4 hours at 130° - 140°C.

D.T.D.687A Type B

Group 1. Planishing, stretching, and artificial ageing as for Type A, Group 1.

Group 2. Heavy planishing (10% reduction); stretching and artificial ageing, as for Type A, Group 1.

D.T.D.687A Type C

Group 1. Planishing and stretching, as for A1, followed by artificial ageing for 12 hours at 130° - 140°C.

Group 2. Heavy planishing (10% reduction), stretching, as for A1, followed by artificial ageing for 12 hours at 130° - 140°C.

75ST Type A

Group 1. Planishing and stretching, as for D.T.D.687A, A1, followed by artificial ageing for 24 hours at 115° - 127°C.

Group 2. Roller levelling and stretching, as for A1, followed by artificial ageing for 8 hours at 130°- 140°C.

75ST Type B

Group 1. Planishing and stretching, as for Group 1, followed by artificial ageing for 24 hours at 115° - 127°C.

Group 2. Heavy planishing, (10% reduction), stretching as for Group 1, followed by artificial ageing for 24 hours at 115° - 127°C.

75ST Type C. As for 75ST Type B.

Northern Aluminium Co., Ltd. Sheets of 16 S.W.G., 10 S.W.G. and 3/16 in. were provided, the following being the cast analyses.

| | Cu | Mn | Mg | Fe | Si | Zn | Ti | Cr |
|---|---|---|---|---|---|---|---|---|
| 16 S.W.G. | 1.43 | 0.28 | 2.47 | 0.33 | 0.22 | 6.16 | 0.06 | 0.13 |
| 10 S.W.G. | 1.42 | 0.29 | 2.48 | 0.31 | 0.17 | 6.10 | 0.04 | 0.12 |
| 3/16 in. | 1.43 | 0.27 | 2.47 | 0.36 | 0.17 | 6.10 | 0.04 | 0.12 |

The sheets were solution treated at 467°C and precipitated for 12 hours at 133°C. The following manufacturing details were supplied by the firm:-

| | 16 S.W.G. | 10 S.W.G. | 3/16 in. |
|---|---|---|---|
| Size of ingot | 6" × 20" × 21" | 6" × 20" × 21" | 8" × 28" × 20" |
| Hot rolled to | 3/16 in. | 3/16 in. | $\frac{1}{4}$ in. |
| Annealed at | 3/16 in. | 3/16 in. | - |
| Cold rolled to | 0.064 in. | 0.128 in. | 0.1875 in. |

This material was taken from ordinary production runs.

Whitehead Metals Inc., U.S.A. Sheets supplied in 16 S.W.G. and 10 S.W.G.

No details of analyses or manufacturing processes available.

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## Results of some Strength Tests on the sheet Materials in the "as received" Condition

Note: "L" is abbreviation for "Longitudinal", i.e. parallel to length of 6 ft × 3 ft sheet.

"T" is abbreviation for "Transverse", i.e. parallel to width of 6 ft × 3 ft sheet.

| Manufacturer and Specification | Gauge | Analysis | Proof Stress Tons/sq.in. | | U.T.S. Tons/sq.in. | | Elongation % | | P.S./U.T.S. | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | L | T | L | T | L | T | L | T |
| The British Aluminium Co. Ltd. D.T.D.687 | 10 S.W.G. | A1 | 28.0 | 25.5 | 31.3 | 31.1 | 11 | 10 | 0.90 | 0.82 |
| | | A2 | 28.7 | 24.5 | 32.4 | 30.9 | 12 | 12 | 0.89 | 0.79 |
| | | B1 | 32.6 | 28.6 | 36.4 | 34.7 | 9 | 9 | 0.90 | 0.83 |
| | | B2 | 33.2 | 28.7 | 36.7 | 34.5 | 8½ | 7½ | 0.91 | 0.83 |
| | | C1 | 34.2 | 30.6 | 37.4 | 35.8 | 8½ | 8½ | 0.92 | 0.86 |
| | | C2 | 33.4 | 29.2 | 37.0 | 35.1 | 8½ | 7½ | 0.91 | 0.83 |
| | 16 S.W.G. | A1 | 28.4 | 25.6 | 32.2 | 30.1 | 11 | 11 | 0.88 | 0.85 |
| | | A2 | 26.6 | 24.5 | 30.3 | 29.6 | 13 | 13 | 0.88 | 0.83 |
| | | B1 | 32.1 | 28.6 | 36.3 | 34.0 | 9½ | 9 | 0.89 | 0.84 |
| | | B2 | 28.7 | 29.2 | 34.9 | 34.4 | 9 | 7½ | 0.82 | 0.85 |
| | | C1 | 31.2 | 29.8 | 35.6 | 34.6 | 7½ | 9 | 0.88 | 0.86 |
| | | C2 | 30.9 | 28.8 | 35.1 | 34.1 | 8 | 7 | 0.88 | 0.85 |
| The British Aluminium Co. Ltd. 75 ST | 10 S.W.G. | A1 | - | - | - | - | - | - | - | - |
| | | A2 | 27.8 | 26.8 | 33.8 | 33.1 | 13 | 11 | - | - |
| | | B1 | - | - | - | - | - | - | - | - |
| | | B2 | 29.0 | 28.2 | 34.8 | 34.0 | 9 | 10 | 0.84 | 0.83 |
| | | C1 | 30.2 | 29.2 | 34.9 | 35.2 | 10 | 10 | 0.87 | 0.83 |
| | | C2 | 32.0 | 27.2 | 36.2 | 34.4 | 9 | 9 | 0.88 | 0.79 |
| | 16 S.W.G. | A1 | - | - | - | - | - | - | - | - |
| | | A2 | 28.0 | 26.5 | 32.6 | 32.4 | 12 | 11 | 0.86 | 0.82 |
| | | B1 | 24.7 | 27.3 | 34.3 | 33.0 | 9½ | 10 | 0.87 | 0.83 |
| | | B2 | 29.5 | 27.7 | 34.6 | 33.4 | 9½ | 9 | 0.85 | 0.83 |
| | | C1 | 29.2 | 27.2 | 34.8 | 33.3 | 10½ | 7½ | 0.84 | 0.82 |
| | | C2 | 30.4 | 27.4 | 35.4 | 32.3 | 8½ | 10 | 0.86 | 0.84 |
| The British Aluminium Co. Ltd. D.T.D.603 | 3/16 in. | - | - | - | - | - | - | - | - | - |
| | 10 S.W.G. | - | 23.0 | 18.9 | 30.4 | 29.8 | 16½ | 15½ | 0.76 | 0.63 |
| | 16 S.W.G. | - | 22.9 | 19.7 | 30.2 | 31.0 | 17 | 17½ | 0.76 | 0.64 |
| The Northern Aluminium Co. Ltd. D.T.D.687 | 3/16 in. | - | - | - | - | - | - | - | - | - |
| | 10 S.W.G. | - | 30.9 | - | 35.5 | - | 10 | - | 0.87 | - |
| | 16 S.W.G. | - | 30.9 | 27.4 | 34.2 | 33.9 | 9½ | 9½ | 0.91 | 0.81 |
| Messrs. James Booth & Co. Ltd. D.T.D.687 | 3/16 in. | - | 32.6 | 28.5 | 36.2 | 36.1 | 9 | 9 | 0.90 | 0.79 |
| | 10 S.W.G. | - | - | - | - | - | - | - | - | - |
| | 16 S.W.G. | - | 32.1 | 36.0 | 35.6 | 35.1 | 8½ | 8 | 0.90 | 0.86 |
| Whitehead Metals Inc., U.S.A. 75 ST | 10 S.W.G. | - | 30.6 | 27.2 | 34.8 | 35.2 | 10 | 9½ | 0.88 | 0.78 |
| | 16 S.W.G. | - | 30.2 | 27.4 | 34.4 | 34.0 | 9½ | 6 | 0.88 | 0.81 |

## APPENDIX III

### Notes on Loading Rig for the Investigation of the Shatter Properties of High Strength Light Alloys

#### General

The rig was designed specifically to investigate the shatter properties of high strength light alloy specimens, under tension and compression, when attacked with 20 mm Ball Ammunition. The rig is hydraulically operated, its main units being an hydraulic jack, a hand pump unit and an electrically operated pump unit.

The layout of the rig is illustrated diagrammatically in Figs.1 and 2, and photographs of the rig and pump units are reproduced in Figs.3 and 4 respectively.

#### Details of Units

Hydraulic Jack

| | | |
|---|---|---|
| Piston diameter | = | 15.62 ins. |
| Piston area | = | 191.62 ins. |
| Piston rod diameter | = | 3.50 ins. |
| Piston rod area | = | 9.62 ins. |

Overall piston travel = 10 ins. approximately.

Hand Pump

Turner Duplex hand pump.

Motor-pump Unit

B.T.H. 3 phase, 400 Volt A.C. Motor

rated 3.5 H.P., (Speed 0 to 2,500 R.P.M.), used with a Plessey line feed pump.

#### Loading Data

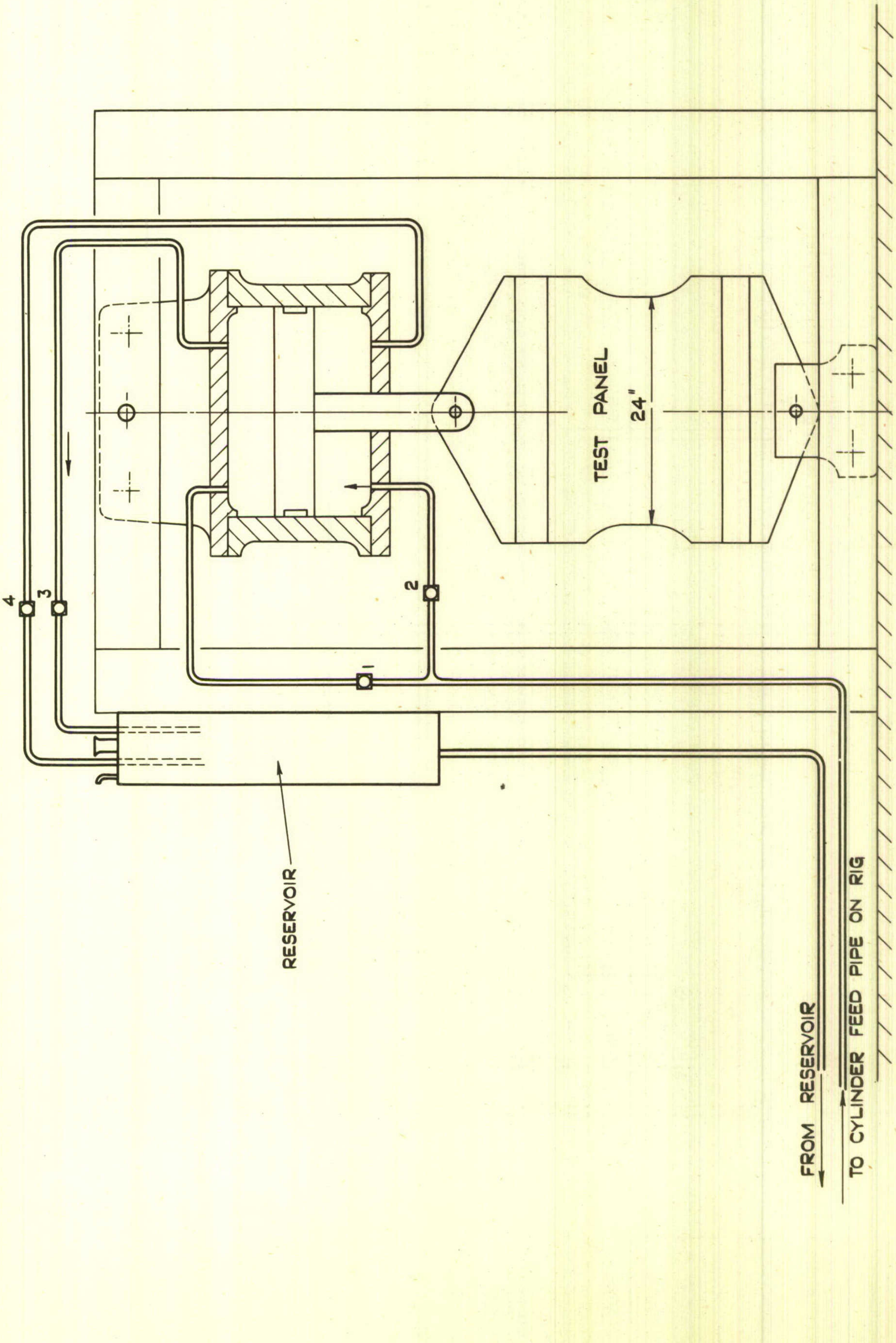
| | | |
|---|---|---|
| Effective piston area in Tension | = | 182.0 sq. in. |
| Effective piston area in Compression | = | 191.62 sq. in. |
| Maximum Working Pressure | = | 1500 lb/sq. in. |
| Maximum load in Tension | = | 122 tons |
| Maximum load in Compression | = | 128 tons |

Conversion factors are:-

In Compression: Gauge reading (lb/sq. in.) × 0.0853 = Total load in Tons or Total load in Tons × 11.7 = required gauge reading.

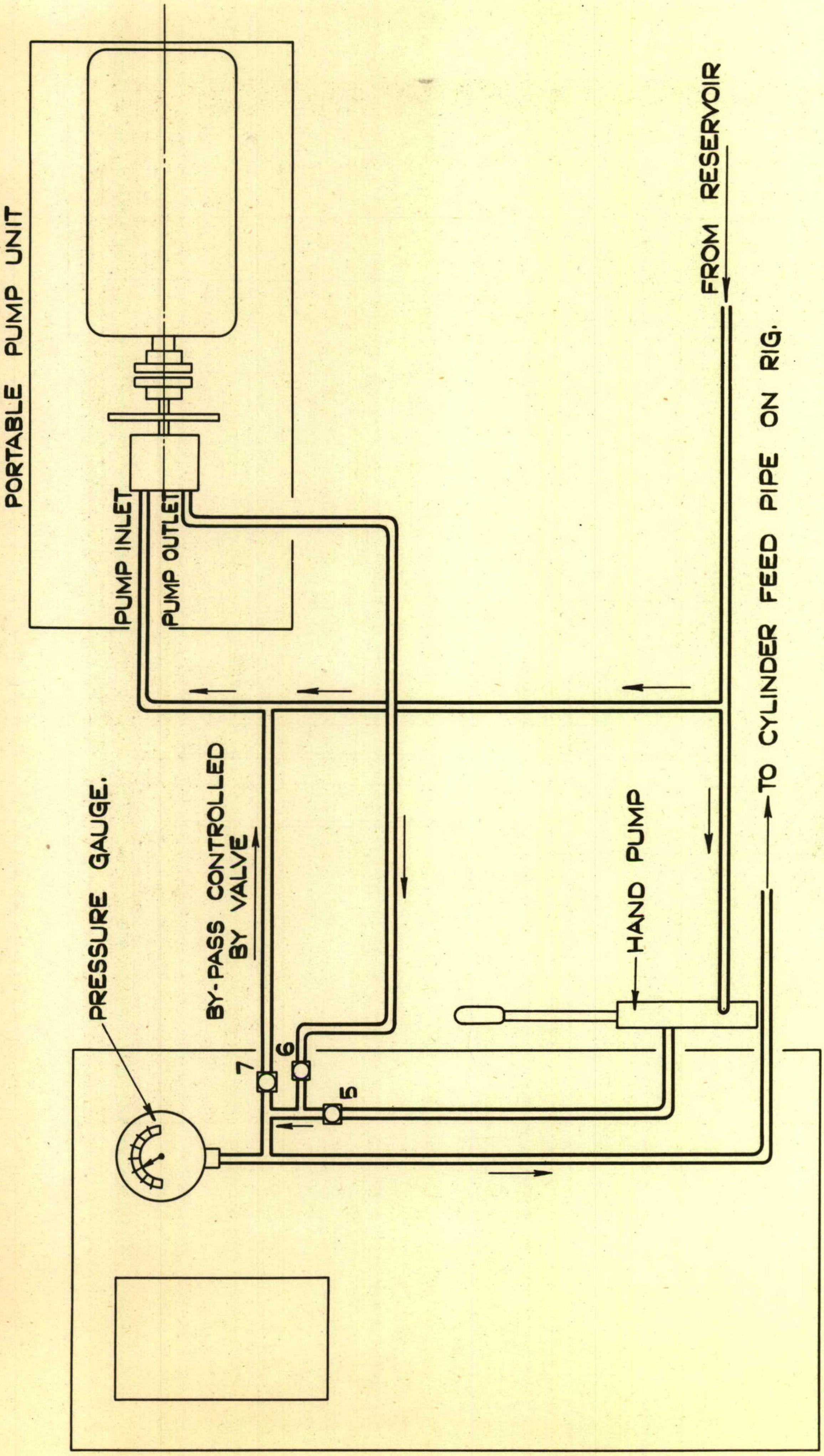
In Tension: Gauge reading (lb/sq. in.) × 0.0813 = Total load in Tons or Total load in Tons × 12.3 = required gauge reading.

FIG. I.




SEE FIG. 2 FOR ELECTRICAL PUMP UNIT.

FIG. I. DIAGRAMMATIC LAY-OUT LOADING RIG.




SEE FIG. 1 FOR LAY-OUT OF EQUIPMENT FOR RIG.

FIG. 2. DIAGRAMMATIC LAY-OUT OF PUMP UNIT.

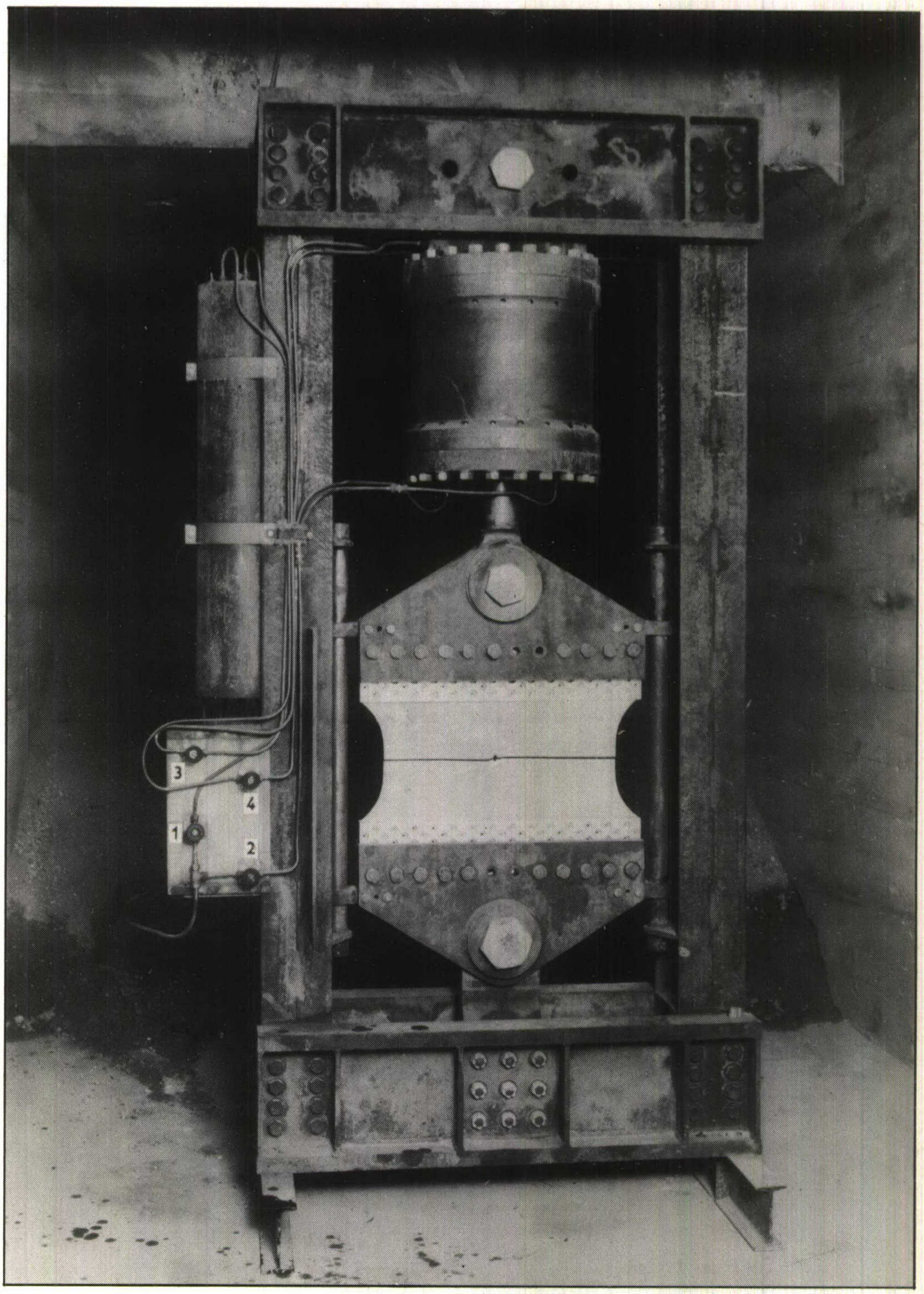



**FIG.3.** Test Rig for Loading Specimens.

Specimen Shown in Position After Attack with .303 Calibre Ammunition.

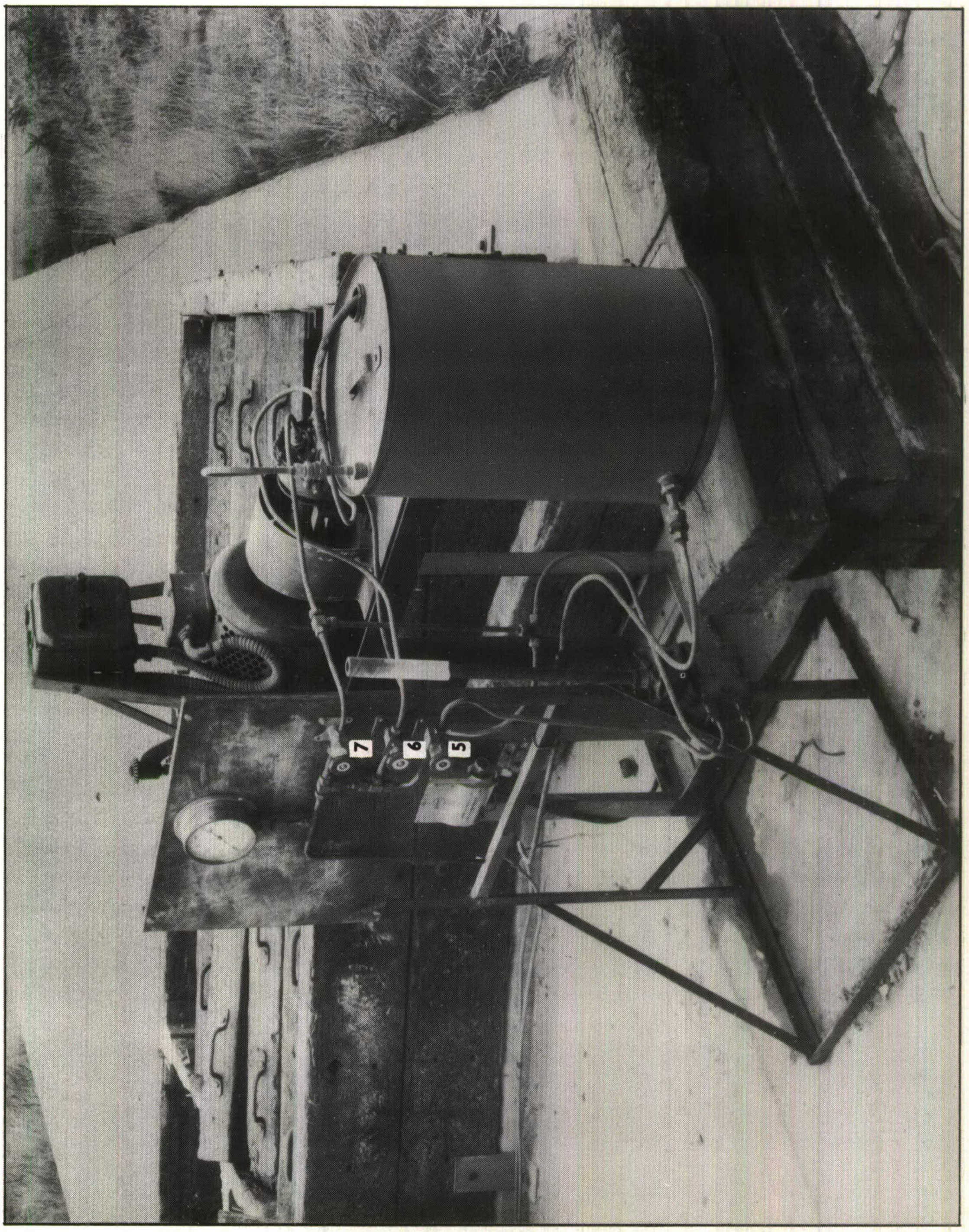
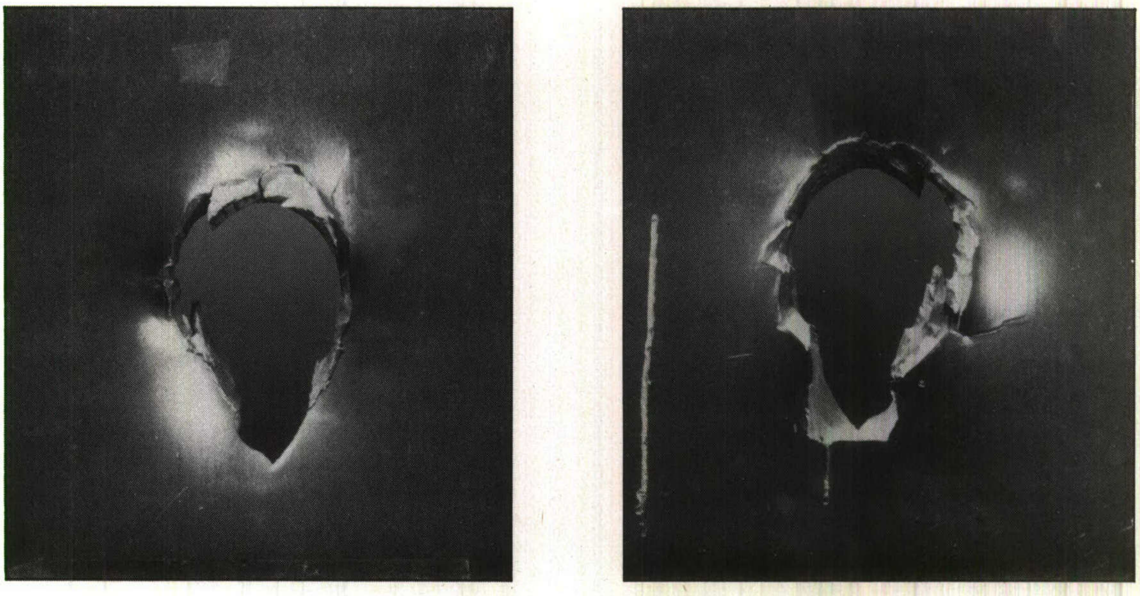
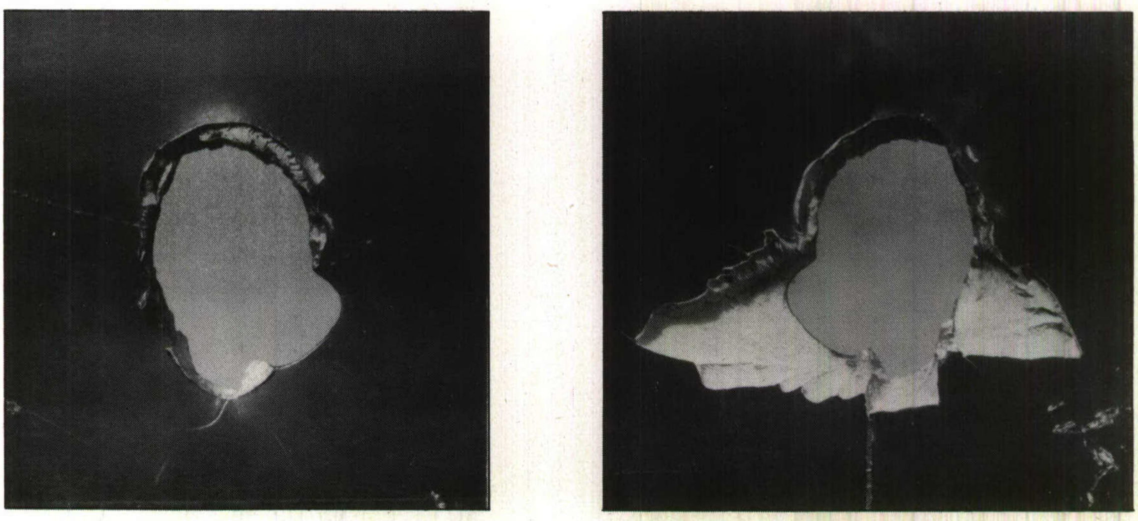



FIG.4. Pump Unit for Hydraulic Loading Rig.



ENTRY **a.** Analysis A1. EXIT

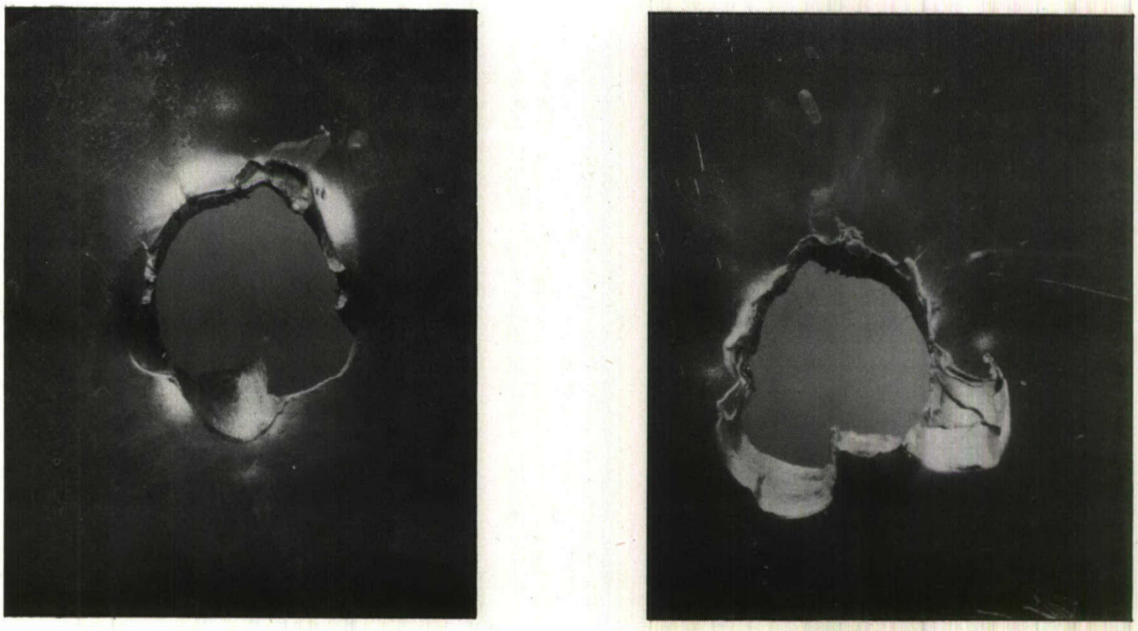
ENTRY **b.** Analysis B1. EXIT



ENTRY **c.** Analysis C1. EXIT

**FIG.1.** Unstressed Plates of D.T.D.687 Attacked with 20 mm. Solid Shot at 60° to the Normal.
Plate Thickness - 3/16 in.
Manufacturer- British Aluminium Co. Ltd.

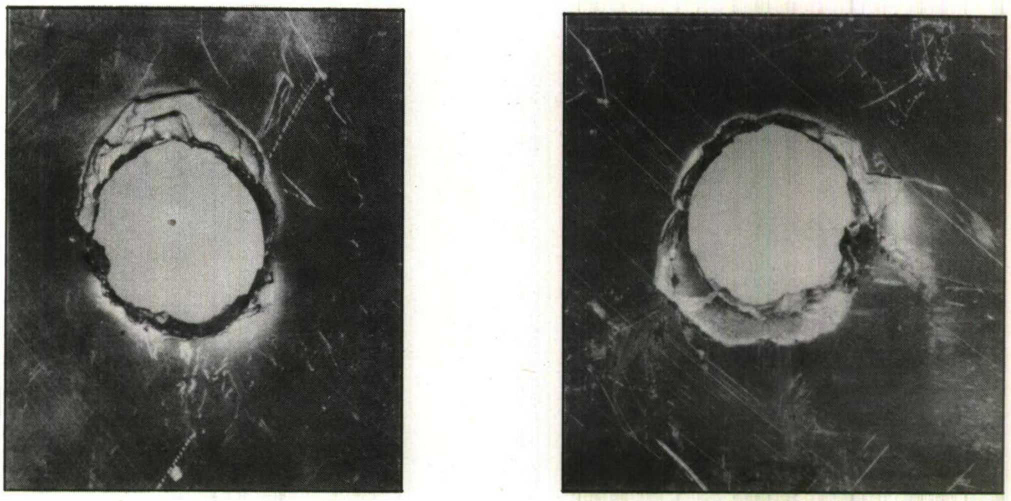
ENTRY **a.** Analysis A1. EXIT



ENTRY **b.** Analysis B1. EXIT

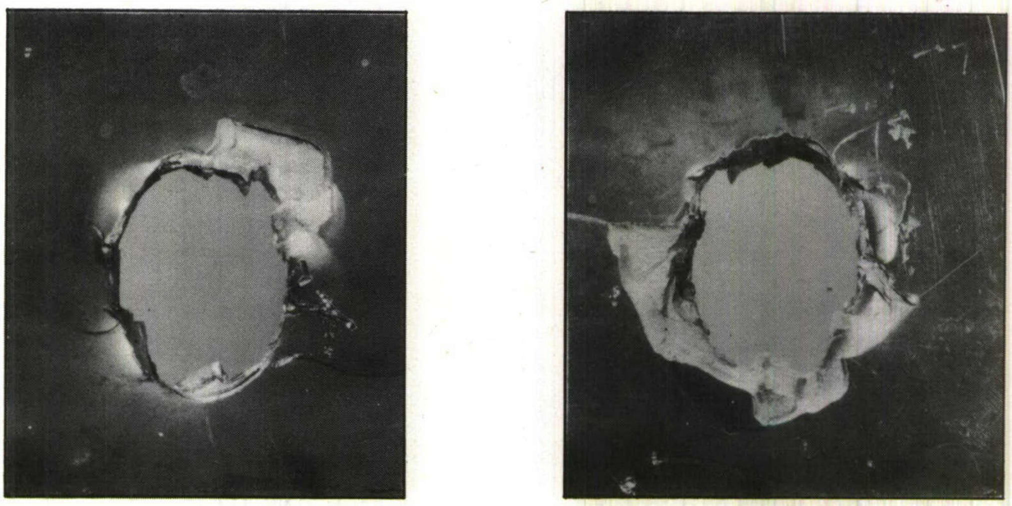
ENTRY **c.** Analysis C1. EXIT

**FIG.2.** Unstressed Plates of 75 ST Attacked with 20 mm Solid Shot at $60^{\circ}$ to the Normal.
Plate Thickness - 3/16 in.
Manufacturer - British Aluminium Co. Ltd.



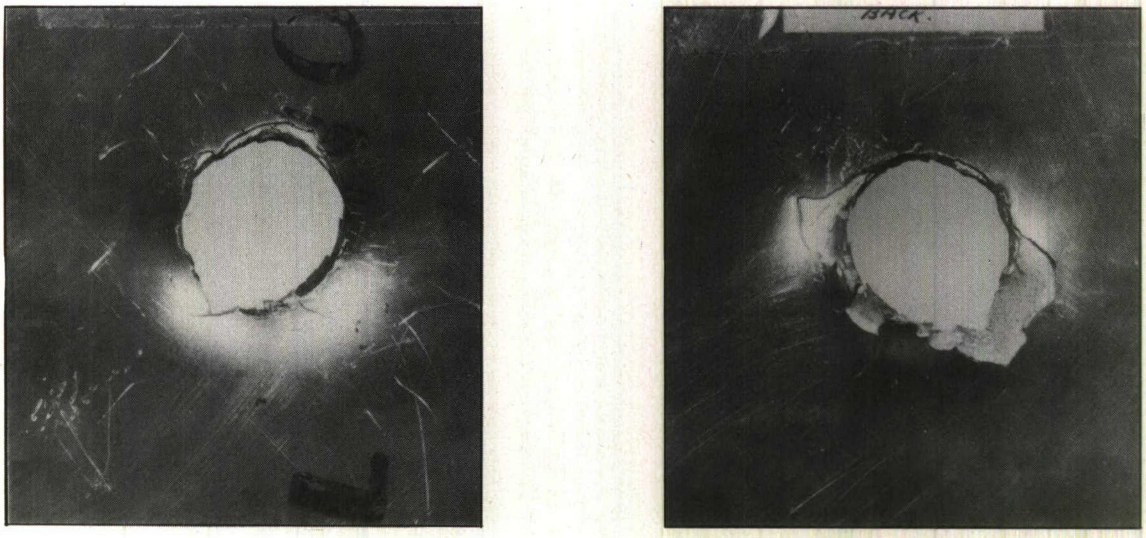
ENTRY EXIT

FIG.3. Unstressed Plate of D.T.D.687 Attacked with 20 mm Solid Shot at 45$^{o}$ to Normal.
Plate Thickness - 3/16 in.
Manufacturer - Northern Aluminium Co. Ltd.



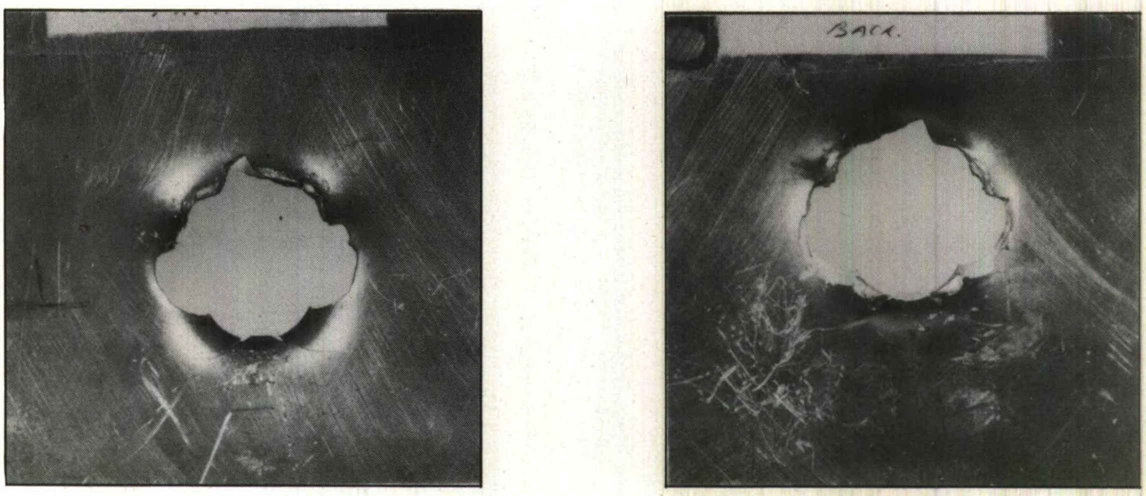
ENTRY EXIT

FIG.4. Unstressed Plate of D.T.D.687 Attacked with 20 mm Solid Shot at 45$^{o}$ to Normal.
Plate Thickness - 3/16 in.
Manufacturer - Messrs. James Booth & Co. Ltd.




ENTRY EXIT

**a** Plate Thickness - .128 in. (10 S.W.G.)




ENTRY EXIT

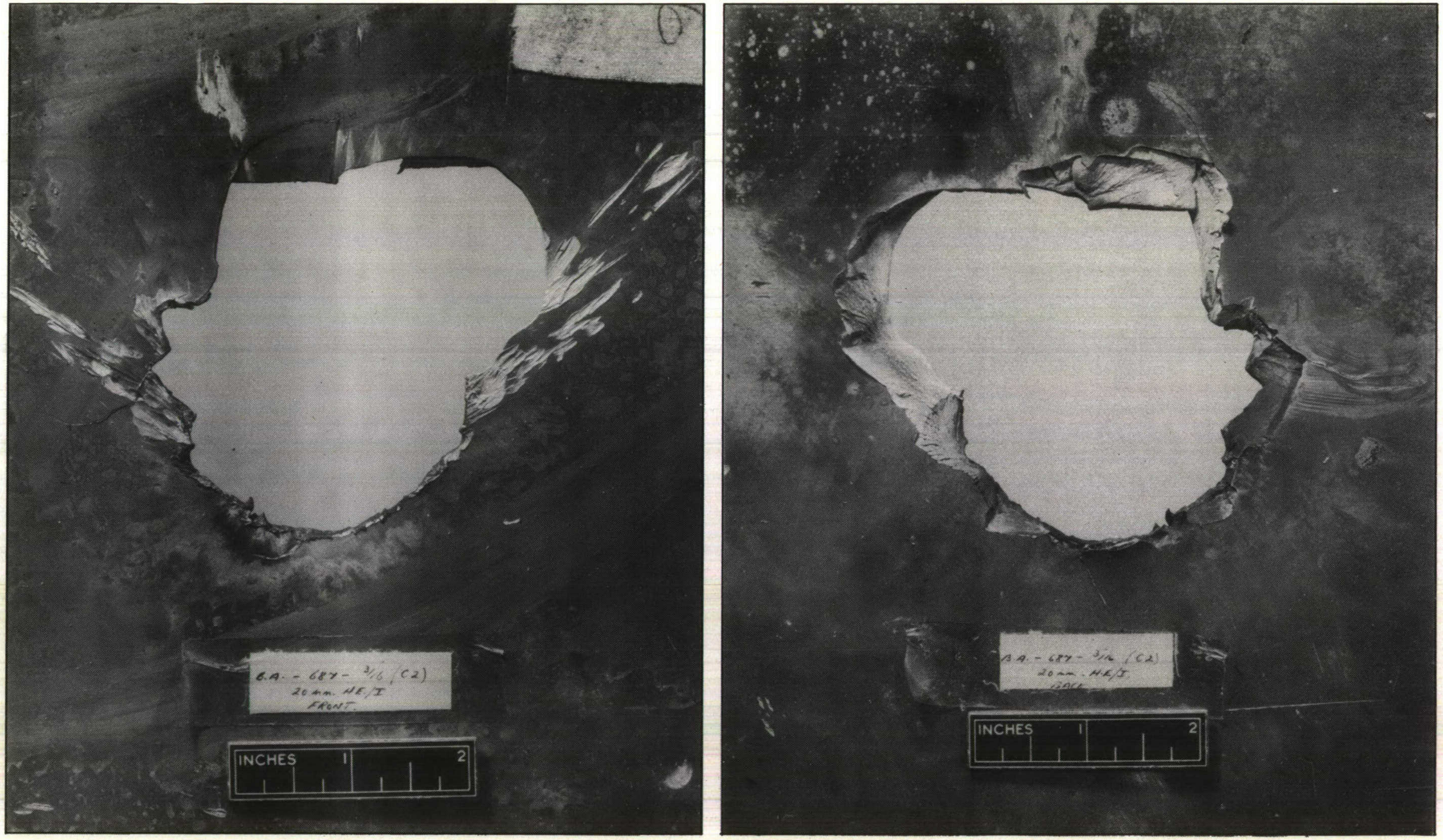
**b** Plate Thickness - .064 in. (16 S.W.G.)

**FIG.5.** Unstressed Plates of D.T.D.687 Attacked with 20 mm Solid Shot at 45° to Normal.
Plate Manufacturer - Northern Aluminium Co. Ltd.


ENTRY **a** Analysis A1. EXIT

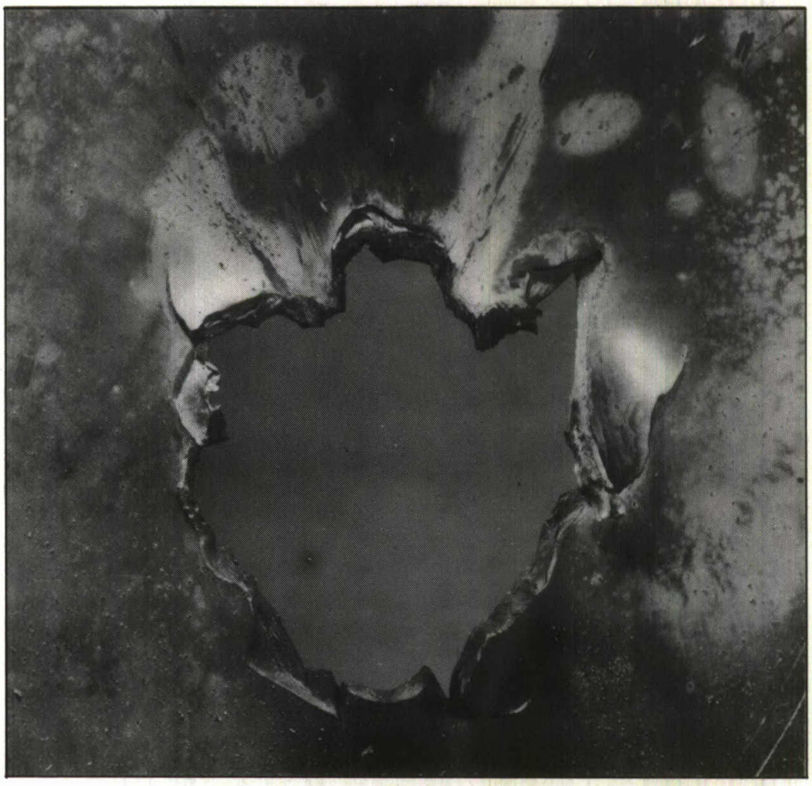

ENTRY **b** Analysis B2. EXIT

**FIG.6.** Unstressed Plates of D.T.D.687 Attacked Directly with 20 mm Explosive Shell at 45° to Normal.
Plate Thickness - 3/16 in.
Manufacturer - British Aluminium Co. Ltd.

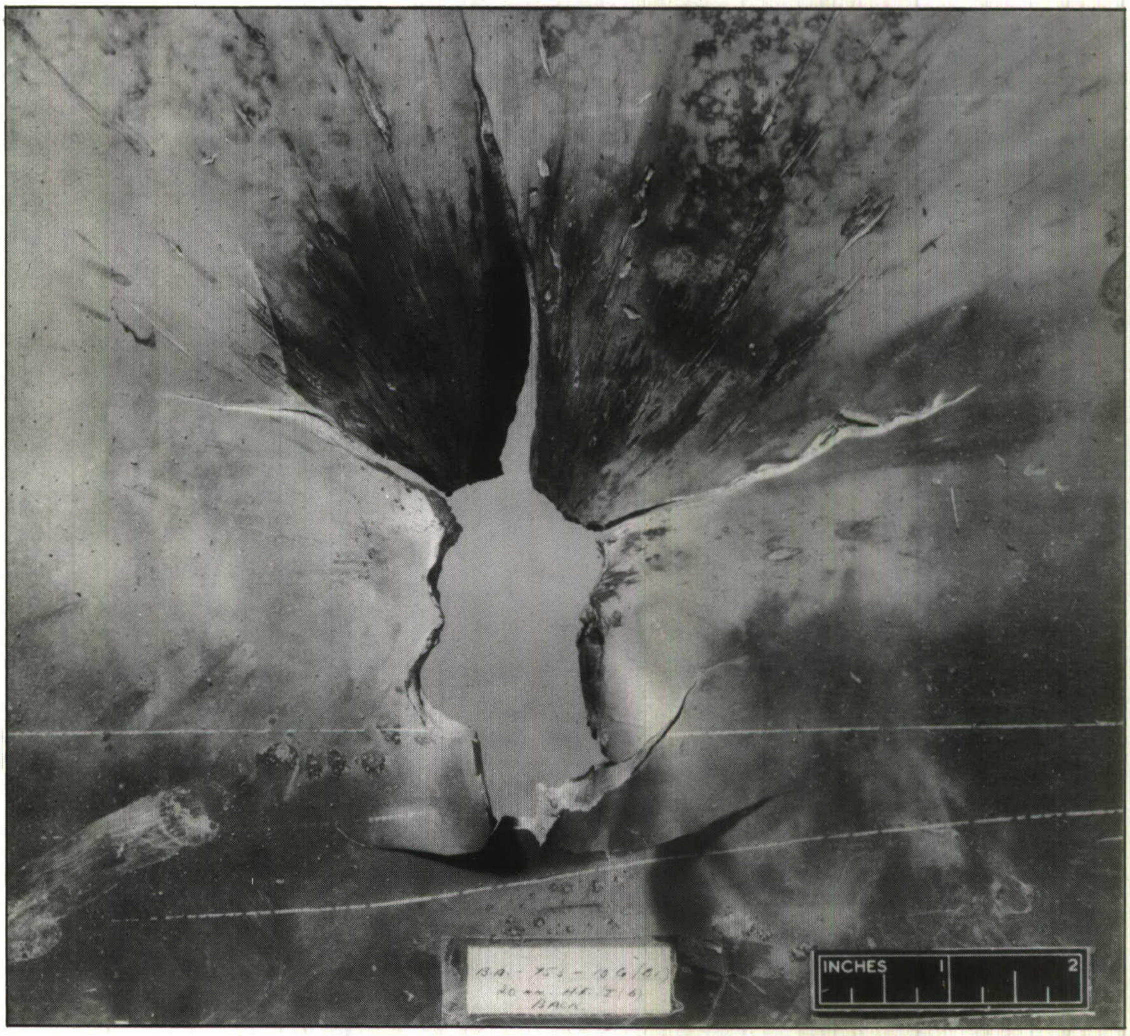



ENTRY Analysis C2. EXIT

**FIG.7.** Unstressed Plate of D.T.D.687 Attacked Directly with 20 mm Explosive Shell at $45^{\circ}$ to Normal.
Plate Thickness - $^{3}/16$ in.
Manufacturer - British Aluminium Co. Ltd.



**a.** Firing 1. Exit Side.
Detonation when Shell is Through Plate.




**b.** Firing 2. Exit Side.
Detonation when Shell is in Plane of Plate.

**FIG.8.** Unstressed Plates of 75 ST (Analysis B1) Attacked Directly with 20 mm Explosive Shell at 45° to Normal.
Plate Thickness - 10 S.W.G.
Manufacturer - British Aluminium Co. Ltd.

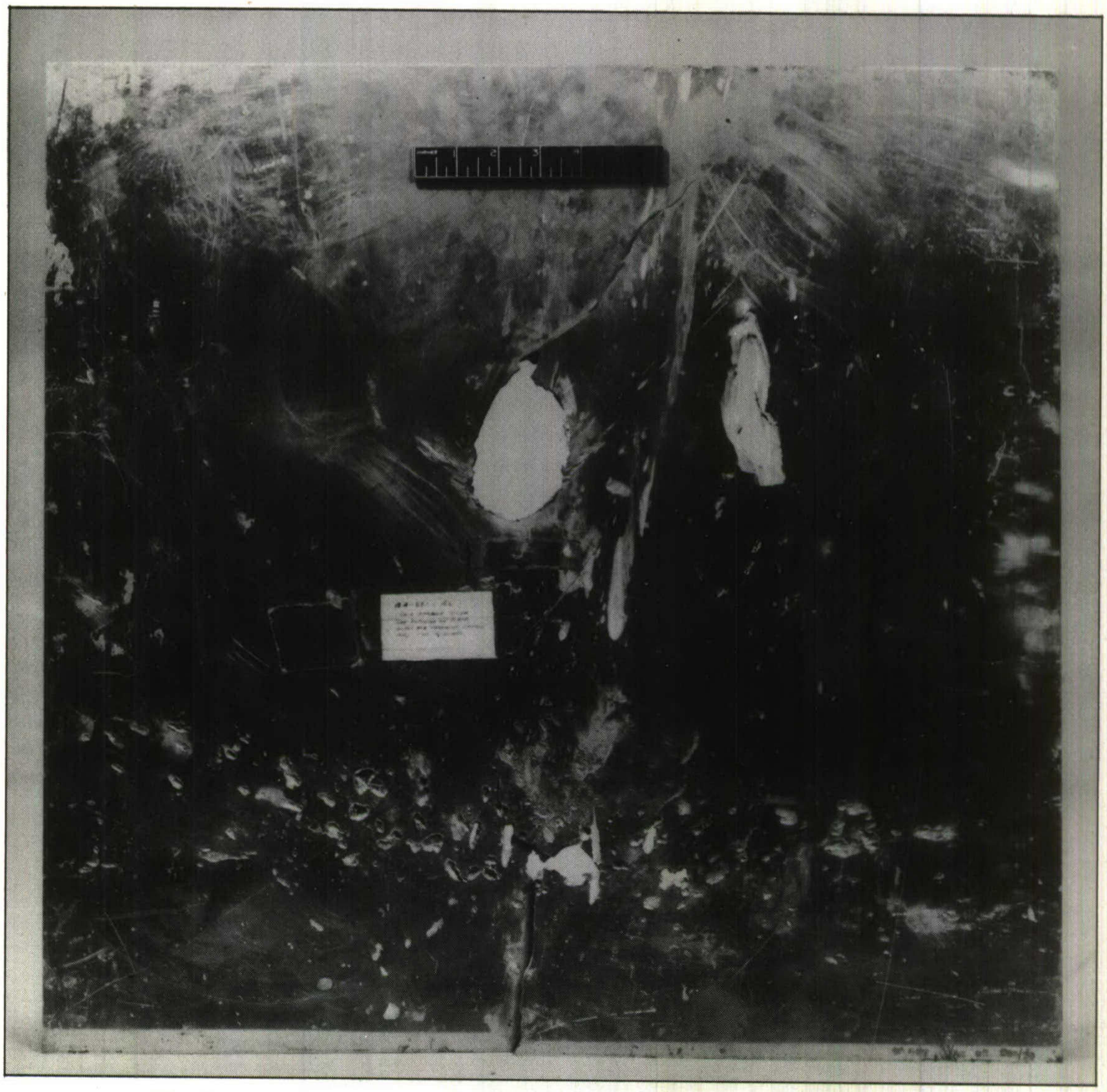
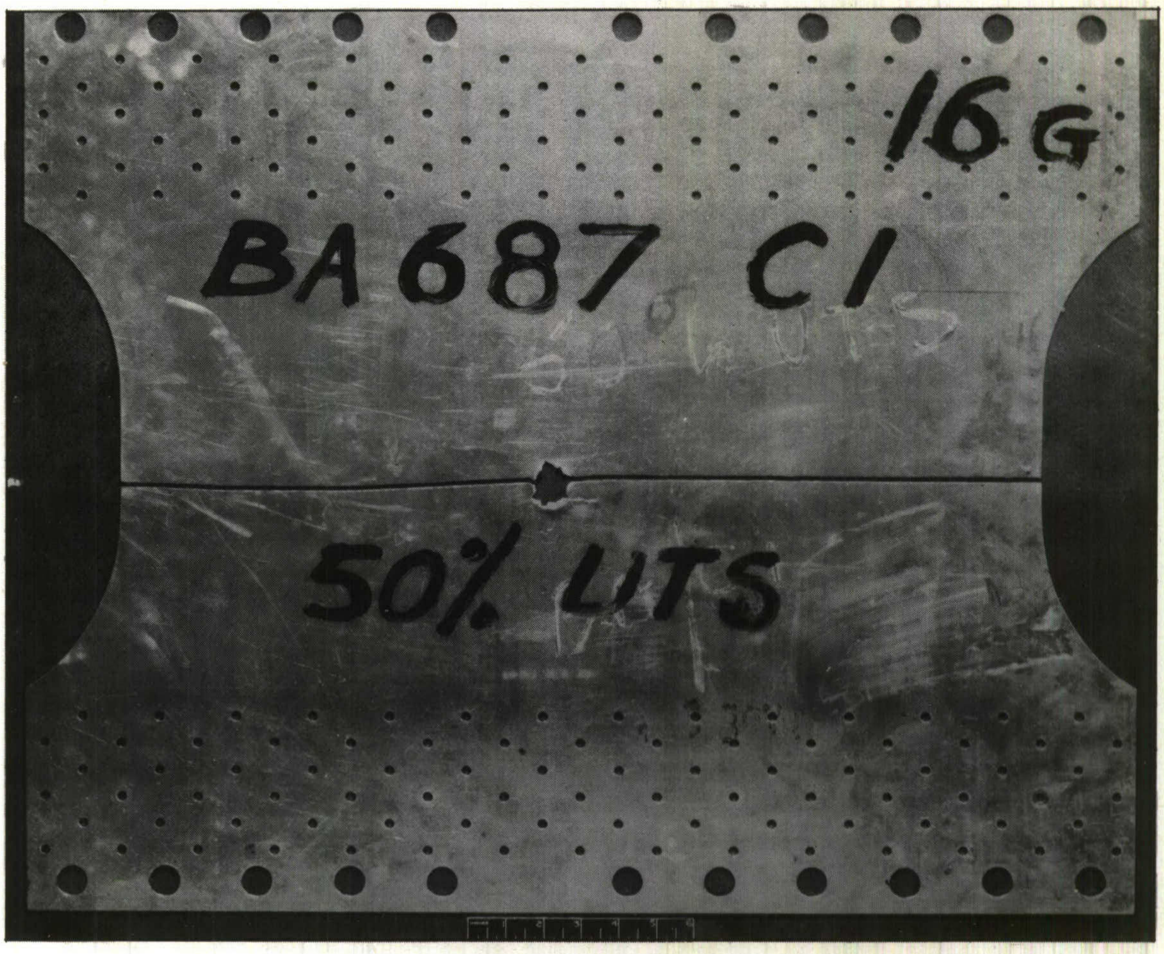
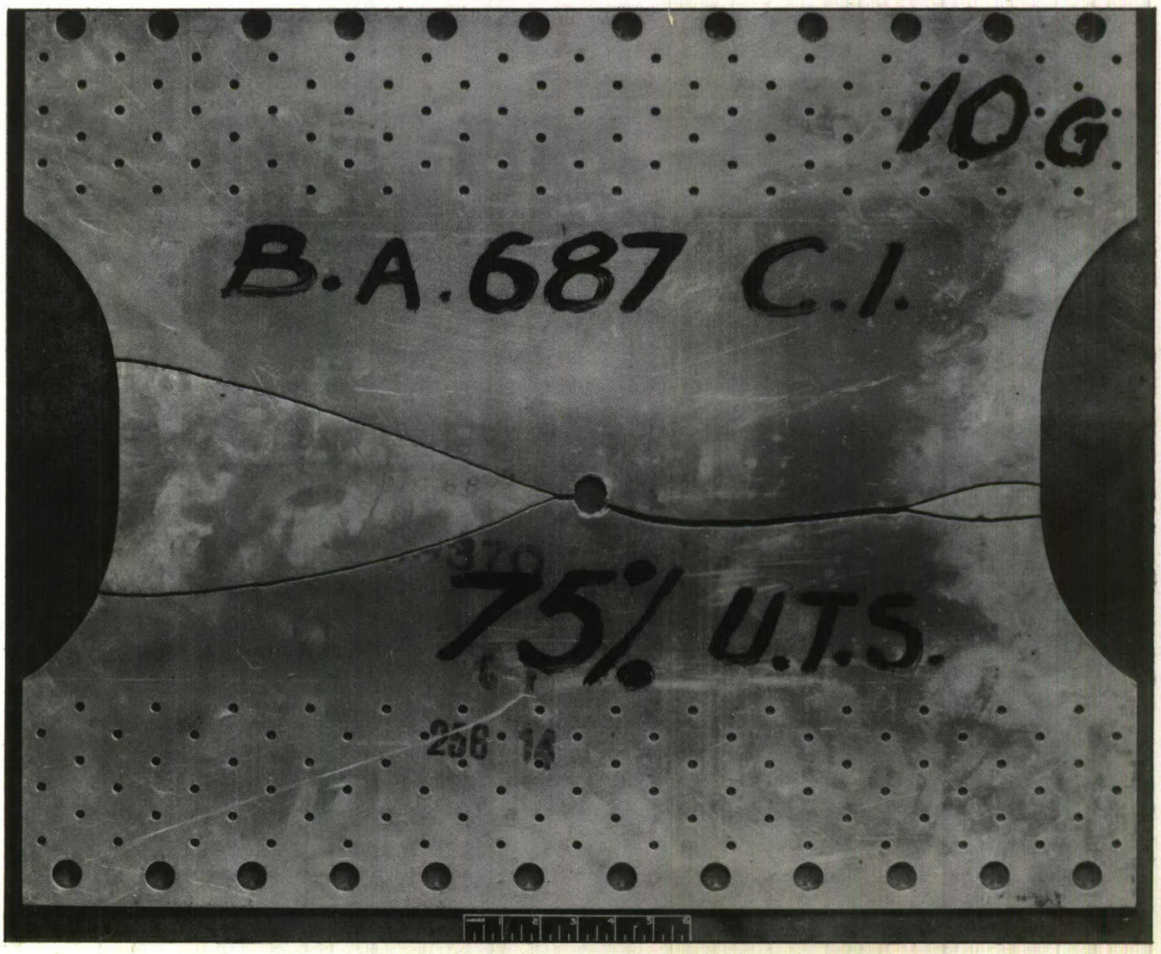


FIG.9. Unstressed Plate of D.T.D.687 (Analysis B2) After Repeated Attacks, Including Exposure to Blast and Fragment Spray from Exploding 20 mm Shell.
Plate Thickness - 3/16 in.
Manufacturer - British Aluminium Co. Ltd.

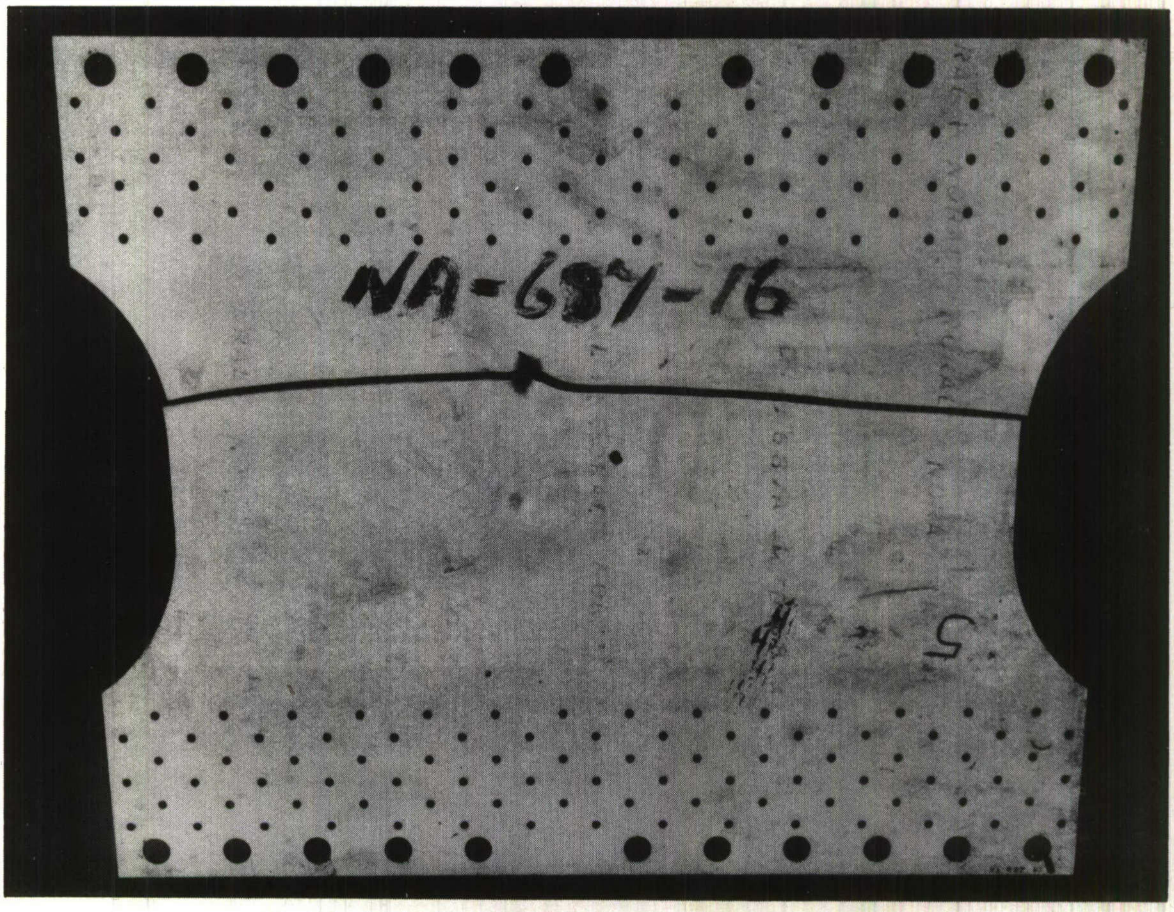



**a** Typical Example of "Split".
16 S.W.G. (.064 in.) Plate to Spec. D.T.D.687 (Analysis C1).
Manufactured By - British Aluminium Co. Ltd.
Stressed To 50% U.T.S.

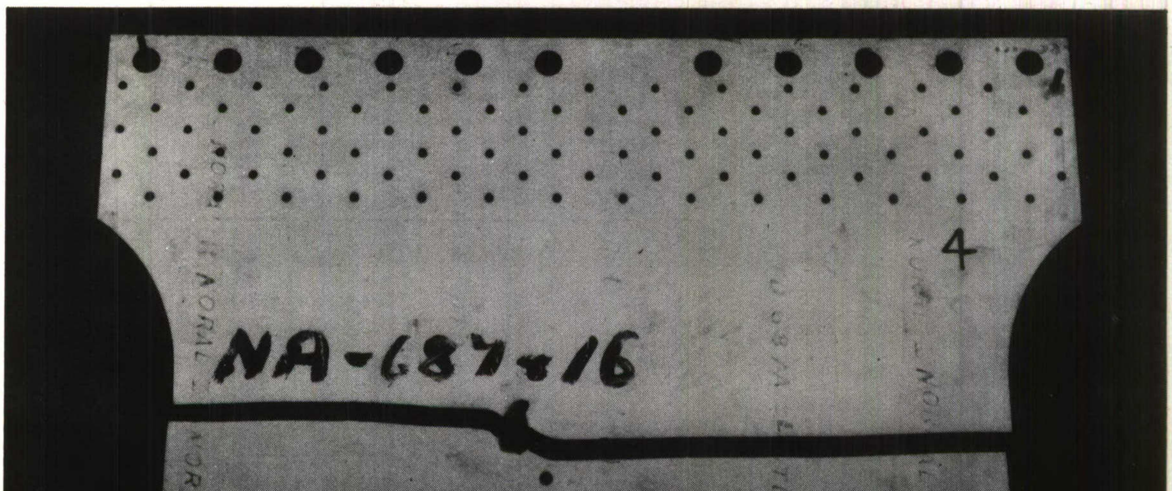



**b** Typical Example of "Shatter".
10 S.W.G. (.128 in.) Plate to Spec. D.T.D.687 (Analysis C1).
Manufactured By - British Aluminium Co. Ltd.
Stressed To 75% U.T.S.

FIG.10. TYPES OF FAILURE OF STRESSED PLATES ATTACKED WITH 20 MM SOLID SHOT.

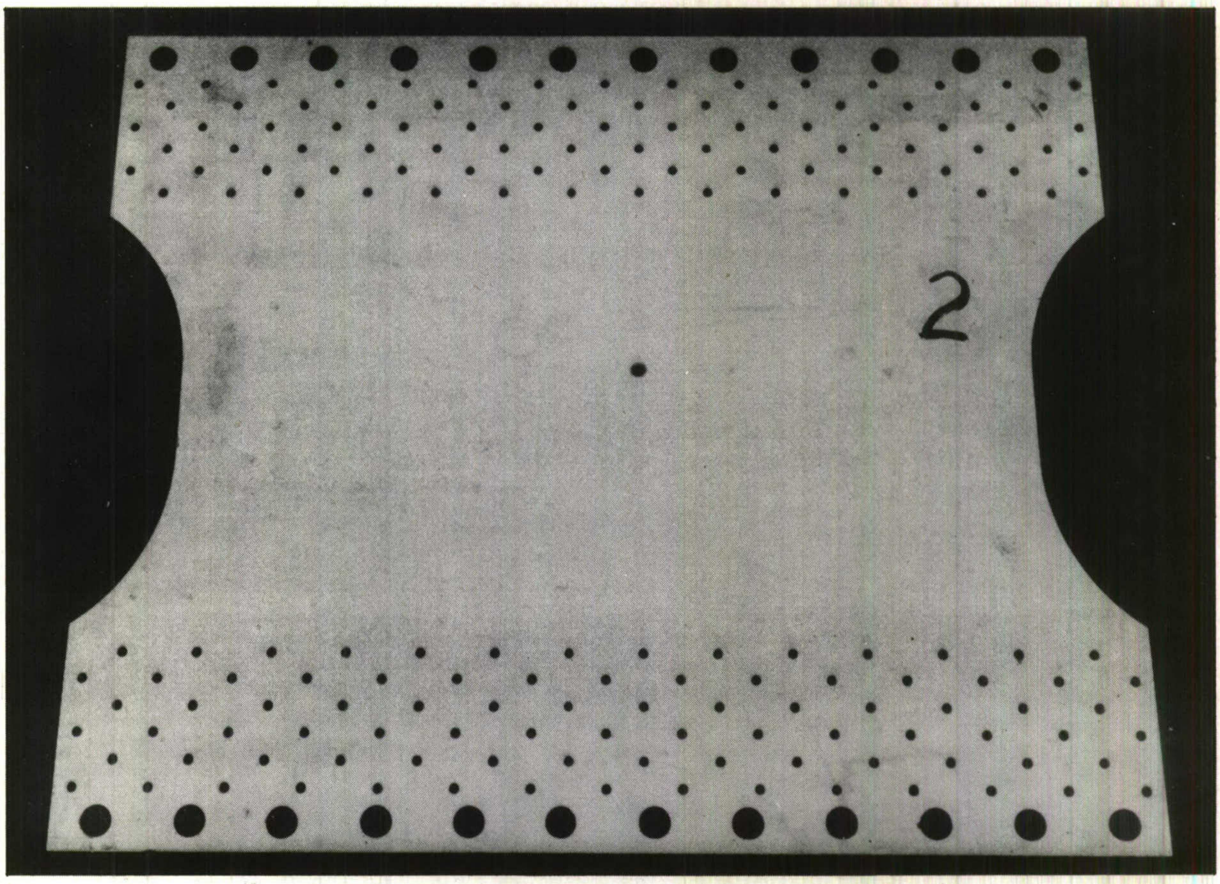



**a** Stressed to 70% U.T.S.
Plate Holed by Fragment and Piece of Sabot
Split Originating at Latter.

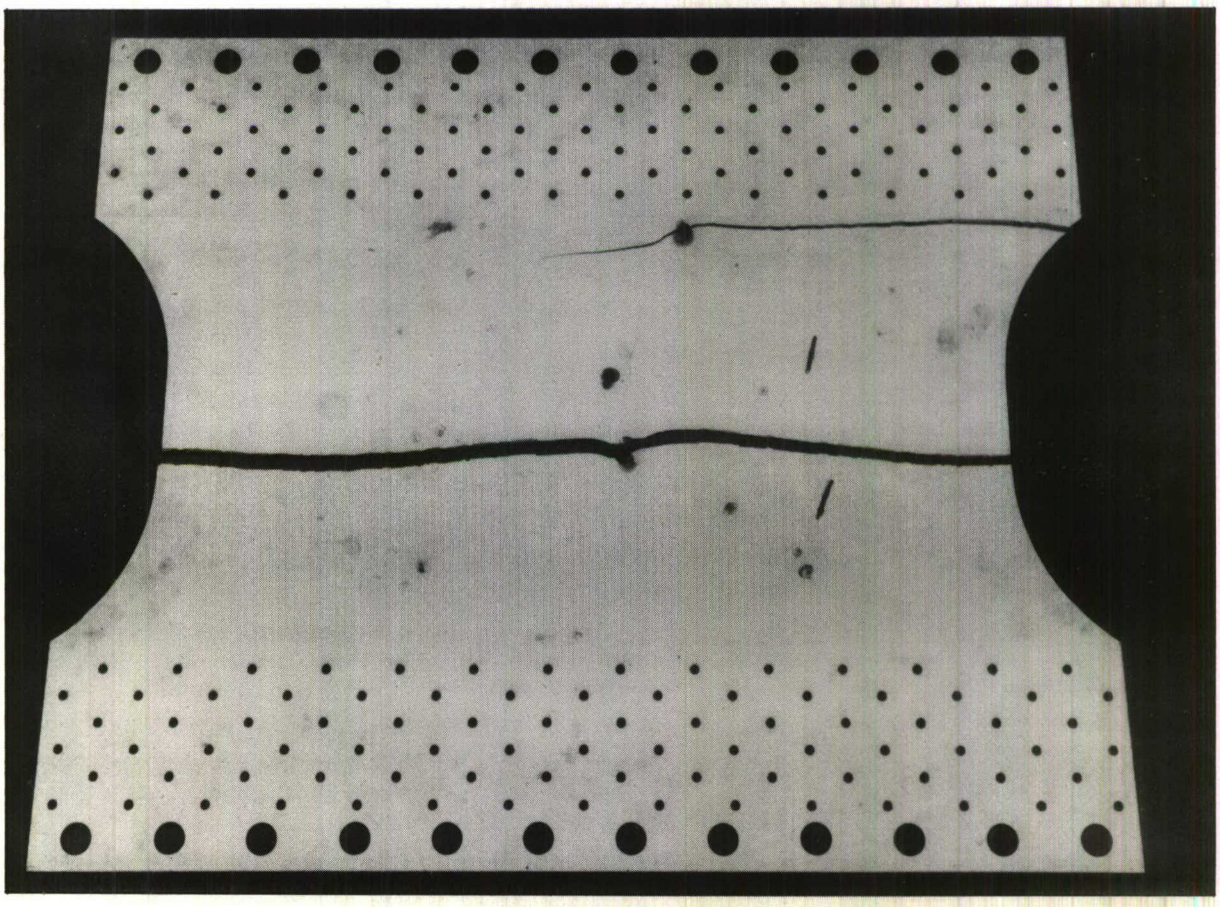



**b** Stressed to 80% U.T.S.
Plate Holed by Fragment and Piece of Sabot and Split.

FIG.11. Results of Fragment Firings Against Stressed Plates
to Spec. D.T.D.687.
Fragment:- 1/25 oz. at 5,200 Ft/Sec.
Thickness of Plates - .064 in. (16 S.W.G.)
Manufacturer - Northern Aluminium Co. Ltd.



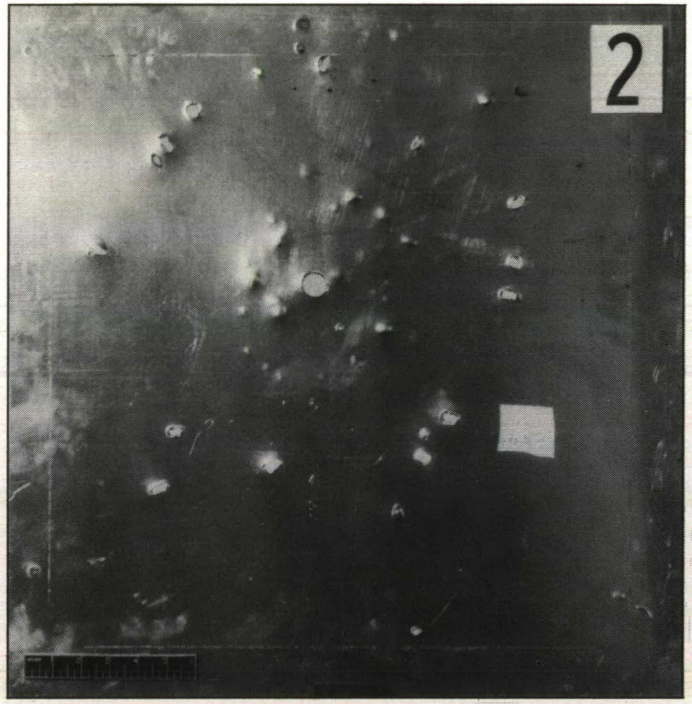

**a** Stressed to 80% U.T.S.
Plate Holed by Fragment Only. - No Failure.



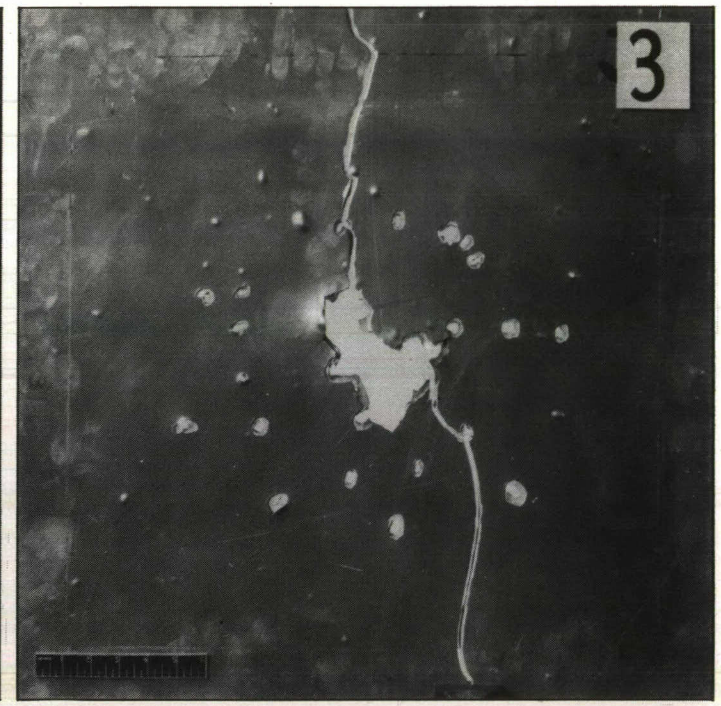

**b** Stressed to 80% U.T.S.
Plate Holed by Fragment and Pieces of Sabot
Crack and Split Originating at Latter Holes.

FIG.12. Results of Fragment Firings Against Stressed Plates to Spec. D.T.D.687 (Analysis C2)
Fragment:- 1/25 oz. at 5,200 Ft/Sec.
Thickness of Plates - .128 in. (10 S.W.G.)
Manufacturer - British Aluminium Co. Ltd.


**a** Manufactured by British Aluminium Co. Ltd. to Spec. D.T.D.687 (Analysis C1) – 3/16 in. Thickness.
"Burster" to Test Plate – 17 in.




**b** Manufactured by British Aluminium Co. Ltd. to Spec. D.T.D.687 (Analysis A2) – 3/16 in. Thickness.
"Burster" to Test Plate – 19 in.




**c** Manufactured by Northern Aluminium Co. Ltd. to Spec. D.T.D.687 – 3/16 in. Thickness.
"Burster" to Test Plate – 13 in.

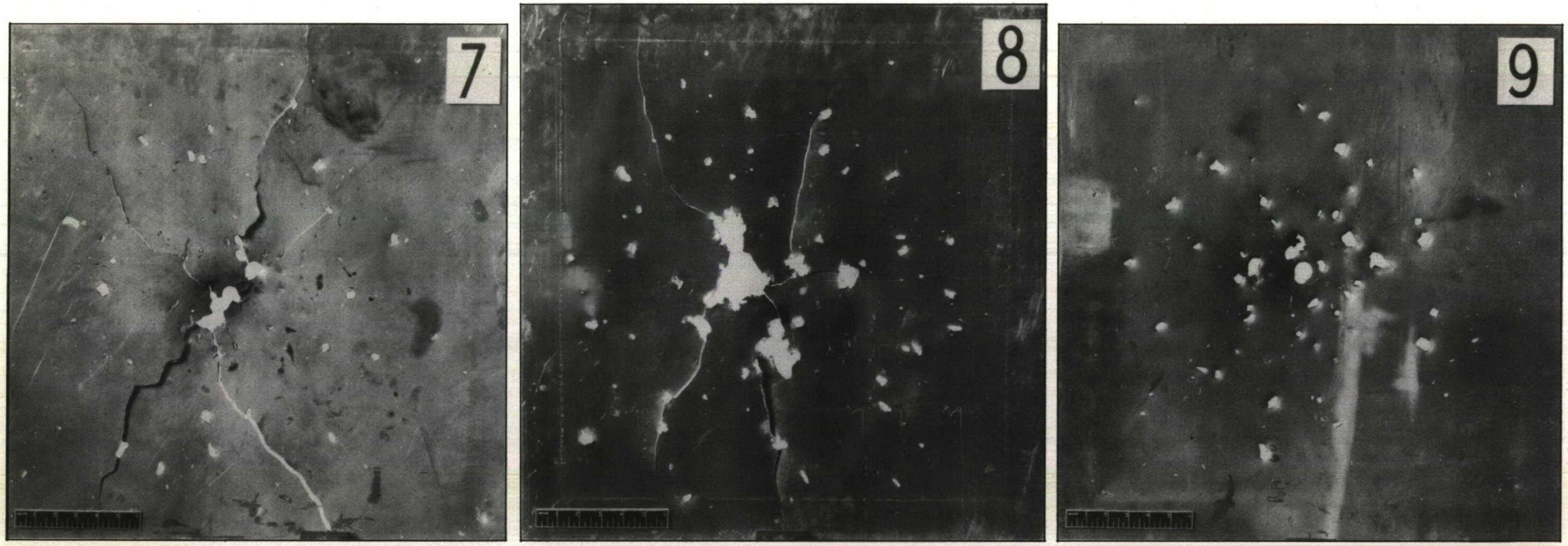
FIG.13. UNSTRESSED PLATES DAMAGED BY REMOTELY DETONATED 20 MM EXPLOSIVE SHELL.


**a** Manufactured by Messrs. James Booth and Co. Ltd. to Spec. D.T.D.687 – 3/16 in. Thickness. "Burster" to Test Plate – 13 in.

**b** Manufactured by Messrs. James Booth and Co. Ltd. to Spec. D.T.D.687 – 3/16 in. Thickness. "Burster" to Test Plate – 19 in.

**c** Manufactured by Northern Aluminium Co. Ltd. to Spec. D.T.D.687 – .128 in. Thickness (10 S.W.G.) "Burster" to Test Plate – 19 in.

FIG.14. UNSTRESSED PLATES DAMAGED BY REMOTELY DETONATED 20 MM EXPLOSIVE SHELL.

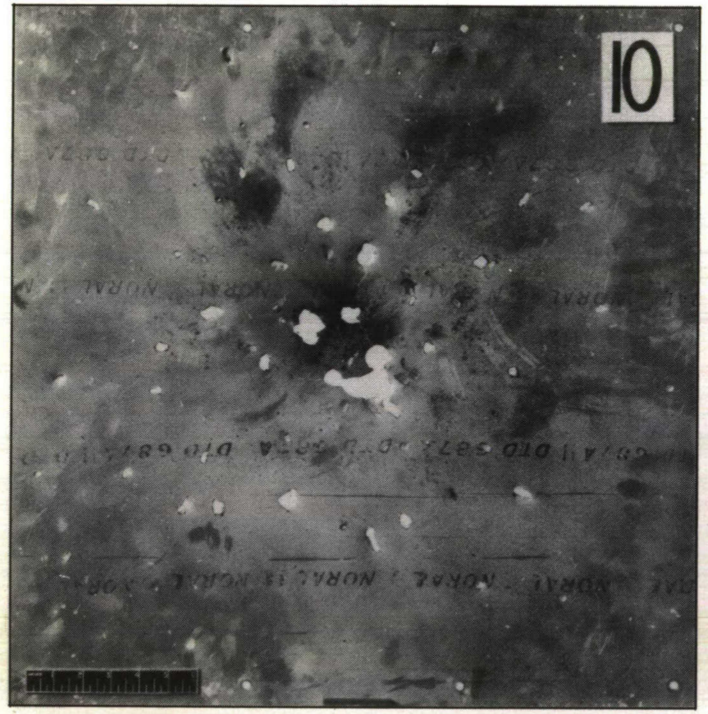



**a** Manufactured by Messrs. James Booth and Co. Ltd. to Spec. D.T.D.687 - .128 in. Thickness (10 S.W.G.) "Burster" to Test Plate - 19 in.

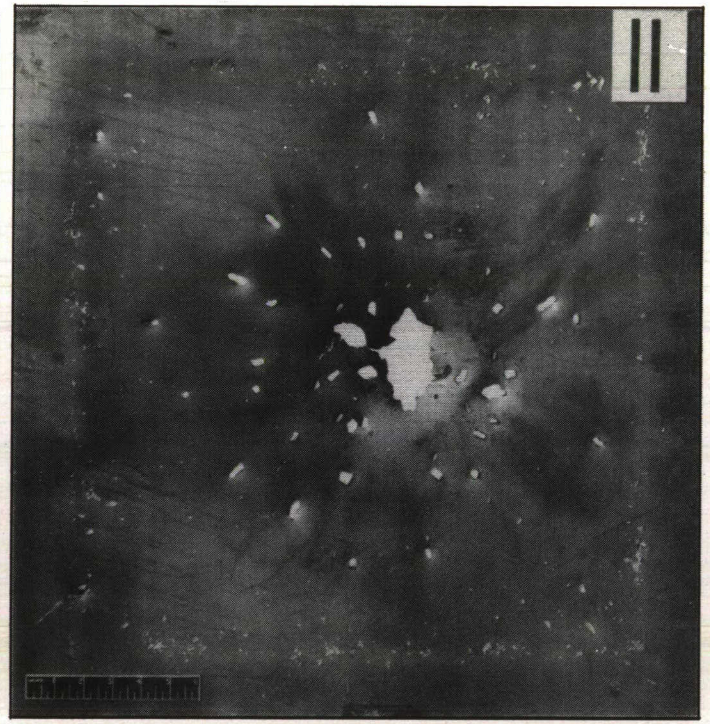
**b** Manufactured by British Aluminium Co. Ltd. to Spec. D.T.D.687 (Analysis C2) - .064 in. Thickness (16 S.W.G.) "Burster" to Test Plate - 19 in.

**c** Manufactured by British Aluminium Co. Ltd. to Spec. D.T.D.603 - .064 in. Thickness (16 S.W.G.) "Burster" to Test Plate - 19 in.

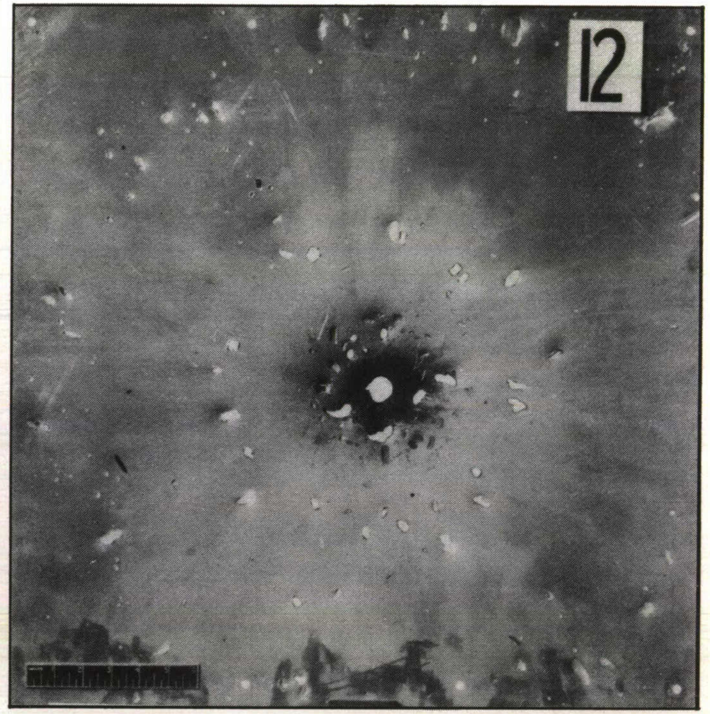
**FIG.15.** UNSTRESSED PLATES DAMAGED BY REMOTELY DETONATED 20 MM EXPLOSIVE SHELL.




**a** Manufactured by Northern Aluminium Co. Ltd. to Spec. D.T.D.687 - .128 in. Thickness (10 S.W.G.) "Burster" to Test Plate - 16 in.




**b** Manufactured by British Aluminium Co. Ltd. to Spec. D.T.D.603 - .128 in. Thickness (10 S.W.G.) "Burster" to Test Plate - 13 in.




**c** Manufactured by British Aluminium Co. Ltd. to Spec. D.T.D.687 (Analysis A1) - .128 in. Thickness (10 S.W.G.) "Burster" to Test Plate - 13 in.

FIG.16. UNSTRESSED PLATES DAMAGED BY REMOTELY DETONATED 20 MM EXPLOSIVE SHELL.

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